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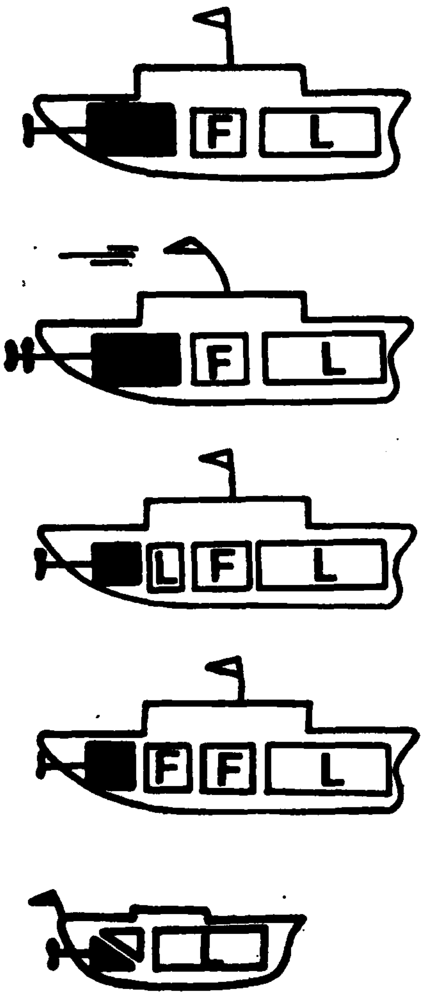

– An Executive Summary –

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Prepared for
The Office of Naval Research
Arlington, Virginia

Under Contracts
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6 **Lightweight Propulsion Systems For Advanced Naval Ship Applications.**

An Executive Summary,

10 Principal Investigator: Simion C./Kuo

Prepared for:

15 The Office of Naval Research, Arlington, Virginia
Under Contract No. N00014-76-C-0542, [redacted] N00014-77-C-0735
Mr. M. Keith Ellingsworth, Program Monitor

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FOREWORD

This executive summary report presents major results obtained from the three-year study on Lightweight Propulsion Systems for Advanced Naval Ship Applications - Parts I, II, and III. The work was performed by the United Technologies Research Center (UTRC) for the Office of Naval Research (ONR) under Contracts N00014-76-C-0542 (for Part I) and N00014-77-C-0735 (for Parts II and III). The Principal Investigator for these contracts was Dr. Simion C. Kuo, and those who assisted in performing the work were: Mr. T. L. O. Horton, Drs. H. T. Shu and C. W. Deane, and Messrs. E. R. Fisher and W. R. Davison. Mr. F. H. Boenig of Power Systems Division, and turbomachinery designers at Pratt & Whitney Aircraft/GPD, both of United Technologies Corporation, provided expert assistance on helium turbine design requirements. Additionally, J. J. Henry, Inc., Professor P. Mandel of MIT, and Dr. P. C. Bertelson provided valuable consulting services on advanced Naval ship characteristics.

As part of the contracted work, two fact-finding trips abroad were made by Dr. Kuo. The first trip to the Federal Republic of Germany and Switzerland was made in July 1976 to discuss the latest developments in closed-cycle gas turbines, high-temperature heat exchangers and gas-cooled reactors, and a comprehensive technical report, UTRC R76-952566-2, was submitted to ONR in November 1976. The second trip was made in October 1977 to Japan to discuss the crucial technological problems relating to open- and closed-cycle gas turbines, naval ship building, and energy research at major heavy industry corporations and selected government agencies. An executive summary report for the trip, UTRC Report R77-952972, was submitted to ONR in November 1977.

The complete report for this study, consisting of the following three parts, has been distributed according to an ONR-suggested list:

Part I - System Studies (UTRC Report R77-952566-5, May 1977)
Part II - Conceptual Design and Reliability Analysis (UTRC Report R78-952979-4, November 1978)
Part III - System Alternatives and Critical Technologies (UTRC Report R79-954176-2, November 1979)

Additionally, six technical papers resulting from the study were published in various conference proceedings and professional journals.

The contract program was initiated with ONR on April 1, 1976 for the Part I - Systems Studies and on August 15, 1977 for the Part II - Conceptual Design and Reliability Analysis as well as the Part III - System Alternatives and Critical Technologies (see Fig. 1). The technical monitors for ONR were LCDR William R. Seng from April 1976 to May 1978 and Mr. M. Keith Ellingsworth thereafter. Valuable guidance and comments received from Mr. Ellingsworth, LCDR Seng, and Mr. John R. Satkowski, Director of Power Program at ONR are gratefully acknowledged.

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SUMMARY

This executive summary report presents the major results of a comprehensive study program to evaluate the technological and economic feasibility of utilizing open- and closed-cycle gas turbines to provide lightweight propulsion power for future Navy surface ship applications. The level of technology considered in this study is that judged by the Contractor to be available during the 1990's.

Naval ship types which could benefit from implementing lightweight propulsion systems were identified and characterized, and applicable propulsion system configurations and power levels compatible with component capabilities were selected. Extensive parametric analyses were made of the performance, weight, and cost characteristics for the baseline propulsion systems, from which the total propulsion-system-plus-fuel weight was then estimated. The payload capabilities and endurance limitations with open- and closed-cycle gas turbine propulsion systems for selected ship types are presented.

Extensive performance, size, and weight analyses were performed for the selected helium heater systems most suitable for integration with the closed-cycle gas turbines for ship propulsion. A conceptual design of an 80,000-shp helium turbine was performed and a preliminary propulsion system layout design for the conceptual high-speed destroyer application was made. Figures showing the power conversion system layout, engine room locations, and overall propulsion system integration with the ship are presented. The reliability characteristics of the reference propulsion system were predicted, and figures showing the dependence of mission reliabilities on different maintenance/repair practices are presented.

Estimates were made of the performance, size, and weight characteristics of selected superconducting and seqmented magnet (SEGMAG) electrical transmissions, and relative technical merits were evaluated for the 80,000-shp propulsion system alternatives using different transmission types. Finally, the crucial technologies and specific components which require development were identified, and test programs, milestones, and cost schedules required to implement the reference closed-cycle gas turbine propulsion system are presented. The open-cycle gas turbine was evaluated from an exploratory viewpoint only, therefore sufficient design data were not produced for extensive comparisons with the closed-cycle propulsion systems.

The study program was conducted by the Energy Conversion Systems group at UTRC under Contracts N00014-76-C-0542 and N00014-77-C-0735 from Power Program Branch of the Office of Naval Research, Arlington, Virginia.

OVERALL CONCLUSIONS

1. Both the open- and closed-cycle gas turbines (OCGT and CCGT) have potential in lightweight ship propulsion systems (LWSPS) for improving mission capabilities (in terms of increased maximum speed or endurance time, or both) of advanced Navy surface ships.

2. With fossil(oil) fuels, the OCGT offers the lowest engine-plus-fuel weight for ships with short-endurance (approximately 50 hours) duty cycles, such as surface effect ships, while the CCGT would be more attractive for ships requiring a longer endurance (100 to 300 hours). For ship missions exceeding approximately 200 hours, a nuclear-powered CCGT would be attractive if the reactor system weight can be held under 15 lb/shp.

3. The performance capability of the CCGT-LWSPS will be limited by the heater (helium) outlet temperature which is approximately 816 C (1500 F) at present. A helium heater sized for an 80,000-shp CCGT based on the "combustion gas generator/gas-to-gas heater" concept has a specific weight of approximately 4.4 lb/shp with a heater efficiency of 87 percent.

4. Among the various naval surface ships evaluated, a conceptual high-speed destroyer of approximately 3500 tons displacement capable of 50/20 knots max/cruise speed would benefit the most from implementing the CCGT-LWSPS. Using two oil-fired 80,000-shp engines, the total propulsion system would weigh 11.4 lb/shp, and the ship payload would be approximately 20 percent of displacement for 150-hr cruise or 10 percent for 100-hr duty cycle operation.

5. Development of a closed-cycle helium turbine propulsion system will require seven to ten years of effort and would cost upwards of $300 million. Based on current observations, the helium heater will be the most costly development component.

RESULTS AND CONCLUDING REMARKS

Systems Study (Part I)

I.1 For closed-cycle gas turbines to be attractive for naval ship propulsion, the heat source specific weight will have to be less than approximately 6 lb/shp for fossil(oil)-fired systems and less than 15 lb/shp for nuclear-powered systems.

I.2 Regenerative and intercooled CCGT operating at turbine inlet temperatures between 1500 and 1700 F and maximum cycle pressures between 580 and 840 psia would be most suitable for LWSPS applications.

I.3 Although turbomachinery technology for unit capacities up to 600,000 shp is currently available, the baseline closed-cycle gas turbines would be limited to 200,000 shp due to constraints in transmission and thrustor capabilities; open-cycle engines would be limited to 50,000 shp because of constraints in the aircraft-derivative gas turbine technology.

I.4 The CCGT power conversion system (excluding the heater) would weigh between 1.5 and 2.5 lb/shp, respectively, for the 200,000 and 40,000 shp systems. The specific fuel consumption would be between 0.35 and 0.38 lb/shp-hr, depending on the turbine inlet temperature, but remains nearly constant at part-load. In comparison, the OCGT system would weigh between 0.96 and 1.7 lb/shp, respectively, for the 50,000 and 20,000 shp systems, and the rated specific fuel consumption would be between 0.38 and 0.4 lb/shp-hr for the output range considered, but significantly higher at part-load (up to 180% of rated value).

Conceptual Design and Reliability Analysis (Part II)

II.1 The helium heater system sized for a 80,000-shp CCGT has an overall package of 4.9 m (16 ft) diameter and 10 m (33 ft) length, and a lifetime of approximately 30,000 hours operation (with outlet temperatures below 1500 F) in the marine environment. Higher outlet temperatures or longer lifetimes for the heater system would be attainable by using the "disposable hot section" concept.

II.2 The reference 80,000-shp closed-cycle helium turbine design incorporating aircraft derivative technology is relatively compact and lightweight compared with industrial-design helium turbines; with an estimated specific weight (turbomachine only) of 0.16 Kg/kW (0.26 lb/shp), the reference CCGT is regarded as suitable for lightweight propulsion system applications.

II.3 On the basis of reliability and of being reasonably compact and lightweight, the tube-in-shell type of heat exchanger with small, bare tubes was selected for the design of the three heat exchangers. The distributed type of heat exchanger layout (as opposed to an integrated warap-around design) was chosen to facilitate maintainability, thereby improving reliability. The heat exchanger package (regenerator, precooler, and intercooler) weighs 0.92 Kg/kW (1.53 lb/shp).

II.4 The conceptual-design 80,000-shp CCGT propulsion system is compact enough to be installed in the engine room allocated without severe integration problems with other propulsion system components; the locations and sizes of the engine rooms were specified for the conceptual high-speed destroyer in accordance with the Naval requirements for ship stability and floodable length.

II.5 The start-up, reverse-thrust, and other operational characteristics of the reference closed-cycle gas turbine propulsion system meet the requirements projected for Naval combat ship operation. Only a small heater and a small helium circulator are needed to keep the recuperator warm to avoid excessive thermal stress during the rapid start-up.

II.6 A CCGT-LWSPS could be more reliable than the conventional steam turbine propulsion system, although both systems must rely on operation with alternate (under distress) system configurations in order to achieve mission reliabilities above the 0.90 level; without the power system "reconfiguration", the reliability ranges would be 0.4 to 0.83 for the CCGT system and 0.1 to 0.4 for the steam turbine system, depending on the types of repair/replacement schedules allowable.

II.7 The estimated capital cost (in 1977 dollars) of approximately $250/shp (including $150/shp heat cost) for the CCGT power conversion system is significantly higher than $72/shp for the OCGT systems. However, saving in fuel cost and longer lifetime expected could make lifecycle cost lower for the CCGT.

System Alternatives and Critical Technologies (Part III)

III.1 Using two 80,000-shp CCGT engines, each driving a high-rpm supercavitating propeller for the 50-knot high-speed destroyer, an epicyclic gear transmission (two needed) offers the highest overall technical merit (179 point rating out of possible 200) closely followed by a segmented magnet (SEGMAG) electrical transmission system (176/200). The former transmission system would provide a propulsion system specific weight of 11.4 lb/shp.

III.2 If CCGTs were used for powering conventional destroyers (35 knots maximum speed), an 80,000-shp engine coupled with two SEGMAG generators to power two SEGMAG motors, each driving a fixed-pitch propeller, would offer the highest technical merit (176/200) compared with other configurations using superconducting electrical (160/200 for AC and 166/200 for DC) or mechanical (157/200) transmission systems.

III.3 Despite the near-constant thermal efficiencies at part-load due to use of inventory control of working fluid for power variation, a CCGT propulsion system can save a substantial additional amount of fuel if an electrical transmission is used instead of a mechanical transmission. In the case of the high-speed destroyer mentioned earlier, the potential fuel saving would be at least 4 percent for duty cycle operation and 16 percent or more for cruise. Potential fuel savings attributable to the use of electrical transmissions will be significantly greater for open-cycle gas turbine propulsion systems because of the poor partload performance of the OCGT coupled with mechanical drives.

III.4 When compared with the superconducting (S/C) transmission systems, SEGMAG transmissions offer the inherent advantages of being less complex in construction, requiring no liquid-helium cryogenic subsystems, and being free from potential failures attributable to the accidental loss of superconductivity. However, the SEGMAG transmission would be slightly heavier than the S/C transmissions, weighing between 2.24 and 3.70 lb/shp (compared with 2.20 and 3.40 lb/shp for S/C system) for thrustor speeds of 580 and 230 rpm, respectively, considered for the high-speed and conventional destroyers.

III.5 The use of an advanced electrical transmission (SEGMAG or S/C) would offer not only the potentially attractive fuel savings indicated above, but also greater flexibility/versatility in Naval ship layout and operation, and reduced ship size without compromising the mission capabilities. However, weight savings for the shorter transmission shafts will not be significant (approximately 0.7 and 0.2 lb/shp, respectively for the conventional and high-speed destroyers) because the heavy-duty outboard shaft can not be reduced in length.

III.6 Implementation of lightweight closed-cycle gas turbine propulsion systems for high-speed Naval ship applications would require development of main-shaft thrust bearings and high-speed thrustors (such as the supercavitating propeller) capable of operating at power levels beyond those of current-technology systems.

III.7 A further understanding of helium flow dynamics and heat transfer characteristics, particularly in the area related to turbomachinery aerodynamics and heat exchanger/ducting pressure losses, represents one of the most critical research efforts in developing viable closed-cycle gas turbine power systems, because these characteristics provide a basis for improved design of all the power system components.

RECOMMENDATIONS

1. The extensive technological information and consistent systems evaluation methodologies developed in this study program should be extended to evaluate the technical merits of open-cycle gas turbines integrated with advanced electrical transmissions for conventional as well as conceptual high-speed destroyer applications.

2. A fossil-fired helium heater system should be designed, built, and tested to provide detailed data for overall propulsion system integration, reliability, and lifecycle cost studies.

3. Detailed designs of lightweight electrical transmissions using SEGMAG and superconducting machines should continue to verify the feasibility of building these machines at power levels suitable for marine propulsion applications.

4. Detailed designs of advanced mechanical transmissions using epicyclic gearboxes should be made for comparison with advanced electrical transmissions.

5. High-speed thrustors should be actively developed for high-speed ship applications in the 1990's.

INTRODUCTION

For Navy planners to successfully meet future challenges, understanding the potential for lightweight ship propulsion systems (LWSPS), their technological and economic feasibilities, and the level of efforts and time required to bring about a practical system would appear a crucial issue indeed. Lighter propulsion systems can be beneficial to Naval ship performance in many ways, including improved strategic and tactical operational capabilities resulting from increased speed and/or endurance time, increased payload or reduction in ship size and cost, as well as independence from refueling in foreign ports. The necessity for studies of lightweight propulsion systems has heightened recently, stemming partly from demands for better ship performance, mission capability, payload, and cost effectiveness, and partly from sky-rocketing fuel prices together with uncertainties in the future Naval fuel demand/supply situation.

Naval propulsion systems have traditionally relied on coal- or oil-burning steam turbines while most current commercial and some Naval ships are powered by lower-power Diesel engines which are more efficient, noisier, and less flexible. Open-cycle gas turbines also have been recognized as offering simple, quiet, and responsive propulsion power for naval combat ship applications. Conventional steam turbine systems offer a multi-fuel capability because of external combustion, but they are too massive for small (less than 6,000 tons displacement) and/or high-speed ship propulsion applications. Future naval propulsion systems will have to be efficient, more reliable, and lightweight yet allowing operation on fuels other than high-grade distillate oils, e.g., coal-derived or other synthetic fuels. In this context, the closed-cycle gas turbine (CCGT) appears to offer considerable advantages because it is easily adaptable to various heat sources, fossil or nuclear, and may offer improved turbomachinery durability because internal components are not exposed to the marine air and fuel environment. In addition, the CCGT system offers compact size and large unit capacity, and its excellent design point and part-load efficiencies would allow a much better overall fuel economy.

The fossil-fired closed-cycle gas turbine concept is not new; many CCGT plants have been operating reliably since 1956. However, no practical CCGT propulsion system has ever been installed and operated aboard a ship, and thus its adaptability to, and reliability for naval ship operation are still uncertain. Unlike the constant-speed land-based plants, CCGT designs for propulsion systems must be compatible with the transmission type as well as the thrustor operating characteristics.

Therefore, the first objective of the program was to conduct a systems study to characterize the performance, size, weight, and cost of selected closed- and open-cycle gas turbine systems. The relative impact that these characteristics will have on selected ship mission capabilities, such as payload fraction and endurance time was evaluated. Using the results of this systems study, a conceptual design was made of a reference CCGT power conversion system, in order to identify the physical dimensions and possible limitations inherent with the propulsion system components, especially the oil-fired helium heater. These results were then used to develop a practical propulsion system layout for investigating the integration of the CCGT-LWSPS with the ship type selected and the level of operational reliability expected.

The potential advantage of advanced electrical transmissions for naval propulsion application, particularly for the high-performance ships, have been well recognized for many years. The impact of these electrical transmissions on the attractiveness of CCGT propulsion systems, and the relative technical merit of alternative propulsion system configurations incorporating different transmissions was identified. Finally, the critical component designs and operational problems for the CCGT-LWSPS were reviewed, and schedules and cost estimates for specific research and development needed to demonstrate the reference CCGT-LWSPS were outlined.

The results of this comprehensive study to assess the technological feasibility and economic characteristics of utilizing CCGT-LWSPS for future advanced Naval ships are presented in this executive summary report in three parts. Part I presents the systems study of lightweight ship propulsion systems utilizing open- and closed-cycle gas turbines. Part II presents the conceptual design and reliability analysis of a reference CCGT-LWSPS. The relative technical merit of alternative CCGT propulsion systems using different mechanical and electrical transmissions, and the critical technologies inherent with the CCGT-LWSPS are described in Part III.

TECHNICAL HIGHLIGHTS

1.0 Results of Part I - Systems Studies

The objective of the Part I study was to perform parametric system analyses of performance, size, weight, and cost characteristics of open- and closed-cycle gas turbine systems utilizing fossil and nuclear (for sensitivity analysis only) heat sources to provide advanced lightweight propulsion power for future Naval ship applications.

1.1 Estimation of Propulsion System Requirements

Approximately 20 ship types currently operating in the United States and abroad were examined to identify those advanced Navy surface ships which could benefit from application of lightweight propulsion systems. Six ship types were selected and characterized. The installed power requirements for these ships (see Fig. 1.1) were estimated from the "clean-hull" or towing power prediction, by allowing for the overall propulsive coefficient (OPC) and auxiliary and hotel power requirements. To estimate overall operating fuel consumption for the propulsion power systems, the duty cycle requirements for each selected ship type were defined.

Many types of thrustors are available but only the five types shown in Fig. 1.2 (fixed-pitch and controllable-reversible-pitch propellers of both subcavitating and supercavitating types, and water jet) appear to meet the performance requirements for all of the operating regimes of the ships selected. The gearbox types and shafting requirements were also analyzed, and the performance, weight, and size characteristics were established. The estimated weight characteristics for the propulsion system components are shown in Fig. 1.3 (thrustors), Fig. 1.4 (gearboxes) and Fig. 1.5 (shafts) for use in the systems study.

1.2 Selection and Definition of Propulsion Plant Alternatives

The lightweight propulsion systems considered in the Part I systems study would utilize fossil- or nuclear-powered Brayton cycle engines integrated with lightweight transmissions and thrustors. To reduce the number of such propulsion system alternatives, a preliminary screening procedure was used to identify the most promising alternative propulsion system configurations. The selection of propulsion systems was based on the level of technology likely to be available in the 1990 time period.

To identify the most promising propulsion systems, a set of general requirements and constraints were established concerning technology level, performance, size, design criteria, operational requirements, environmental effects, and economics, as summarized in Table 1.1. All specific requirements for ranking and then selecting the candidate engine cycles, transmissions and thrustor characteristics were based on these general requirements. Then, the potential improvements in turbomachinery, gearbox, shafting, and thrustor technologies were investigated, and the projected component capability limitations for the propulsion system were identified, as summarized in Table 1.2. In an effort to estimate the attractiveness of Brayton cycle engines for LWSPS application in the 1990s, an evaluation of the critical technologies and their future levels of development was undertaken. The projected progression of turbine inlet temperature for OCGT and CCGT is shown in Fig. 1.6 and Fig. 1.7, respectively.

The three alternative propulsion system configurations selected for evaluation in this study consisted of: an open-cycle gas turbine with a fossil-fueled combustor; a closed-cycle gas turbine receiving energy from a fossil-fired heater; and a closed-cycle gas turbine integrated with a nuclear heat source. The gas turbines were coupled with several mechanical transmission systems and thrustors to provide a large number of potential system arrangements to satisfy different ship performance requirements. The alternative configurations and candidate components are summarized in Fig. 1.8; conceivably each of the configurations could use any of the transmission and thrustor concepts shown to meet specific ship requirements.

Then, five basic arrangments were selected for further study as shown in the left column of the selection matrix (Fig. 1.9) at eight levels of installed horsepower (both OCGT and CCGT). Engine, gearbox and thrustor limitations shown earlier in Table 1.2 were used to assemble compatible packages. Detailed sizing and weight estimates were made for the four OCGT and eight CCGT baseline engines resulting from the selection matrix, as listed on Table 1.3.

1.3 Parametric Analyses of Gas Turbine Performance, Size and Weight

The performance and weight characteristics of open- and closed-cycle gas turbines were investigated parametrically to evaluate their potential application as lightweight propulsion systems for future Navy capital ships. Parametric performance calculations were made for selected cycle configurations to identify promising baseline power conversion systems.

Baseline cycle configurations were selected from available cycles by comparing the capability and/or compatibility for each of the open- and closed-cycle configurations to satisfy the general requirements and constraints given earlier in Table 1.1, with allowance for future technological advances. Extensive parametric performance analyses were made for CCGT systems using the proprietary UTC SOAPP program; Fig. 1.10 shows the parametric CCGT performance results. The sizes and weights of turbomachinery and heat exchangers (not including the heater) were estimated using another computer program; Fig. 1.11 shows the specific weight of the CCGT turbomachinery and the required heat exchangers as a function of unit capacity (which covers the range of Fig. 1.9). These results were then combined with the gearbox and drive shafting characteristics presented earlier to yield estimates of the specific weight of the onboard ship propulsion system, as shown in Fig. 1.12 for the CCGT system; the discontinuity on some of the curves is caused by the change in gearbox, from a nonreversible type to a reversible type, based on gearbox limitations.

For the OCGT system, Fig. 1.13 shows the effect of cycle pressure ratio, turbine inlet temperature and turbine cooling requirements on efficiency and specific power. The relationships of specific weight to output horsepower for different types of OCGT packages are shown in Fig. 1.14. By comparing this data on the basis of weight, the aircraft-derivative engine was chosen over the industrial-derivative type. The estimated specific weight of the OCGT system (engine plus its gearbox and shafting) is presented in Fig. 1.15 as a function of installed horsepower.

The potential benefits of a propulsion system must include consideration of the fuel required to operate a ship over a period of time. Based on the number of hours at each power level corresponding to the speed levels specified by the duty cycle and the part-load specific fuel consumption characteristics shown in Fig. 1.16, the weight of fuel burned on the mission was calculated. The estimated weight of the propulsion system and the fuel required shown in Fig. 1.17 as a function of the vessel's range would indicate that the closed-cycle system plot intersects that of the open-cycle at approximately 110 to 180 hours of endurance, depending on the maximum closed-cycle temperatures. Fig. 1.18 shows the payload (as a percentage of the vessel's total displacement) for the three selected ship types powered by either OCGT or CCGT systems as a function of the endurance and of the assumed heat source weight (both fossil-fired and nuclear).

1.4 Preliminary Engineering Cost Analyses

Factors critical for a realistic cost evaluation of the open- and closed-cycle gas turbine engines were investigated; these factors include operating conditions, size, structure, materials, weight, arrangement, and layout. Different methodologies were developed to estimate the cost of the power conversion systems, transmission system, and thrustors because they require different levels of technology, and each type is in a different stage of technical development.

The procedure used to estimate the cost of future open-cycle gas turbines was based on a survey of typical selling prices as published in the open literature. On the other hand, the cost of the closed-cycle gas turbines (including the heat exchangers, ducting, and support structure, but excluding the heater) was estimated with an existing proprietary UTRC computer code. Fig. 1.19 compares these results in terms of 1976 dollars for all the horsepower levels selected; development costs and evaluation of the effects of market size were not included. The propulsion system equipment and fuel costs were estimated for both OCGT and CCGT propulsion systems installed on three selected types of Naval ships. The capital costs were obtained by summation of the cost data generated while the fuel costs were calculated based on system efficiency, duty cycle, fuel price, and operating time considered. The results are shown in Table 1.4.

1.5 Operational Characteristics and Limitations

When the operational characteristics and limitations of the propulsion system are combined with the ship characteristics, an envelope of ship performance is created. Open-cycle gas turbines allow improvements in vehicle response characteristics as compared to earlier steam plants, but greater attention must be paid to design details which minimize salt ingestion. Closed-cycle systems can offer more flexibility in ship operation because of the improved part-load and off-design fuel consumption characteristics, and should be able to respond faster than the most highly automated steam system.

The quantity of fuel required on a combat ship can be the most significant factor in determining payload or mission capability. For OCGT systems, the installation of an additional smaller engine for operation at low power requirements can reduce fuel consumption at the lowest operational speeds. This type of arrangement, however, would require offset, multiple-reduction gearboxes which are not only heavy but also costly. In CCGT systems, the part-load fuel consumption can be maintained at levels very close to the minimum values when inventory control methods are utilized, as seen in Fig. 1.16. The actual fuel consumption characteristics that can be realized with the inventory control may be compromised in part by the need to modify the gas turbine component efficiency characteristics to account for inventory control procedures.

The projections made above have established the potential performance capabilities and limitations for both open- and closed-cycle engine systems in terms of steady-state operation. Achieving these performance levels in OCGT systems should not require any significant development or modifications of existing control systems. For the CCGT systems to provide the projected excellent part-load performance, however, a new and more complex control of the system components is required; for example, the inventory control concept requires the timely discharge, storage, and recharge of the working gas to the system, and the helium heater and the several heat exchangers also must be monitored and controlled.

Response characteristics of aircraft-derivative OCGT are generally much quicker than those required for ship operation. A marine OCGT can accelerate from idle to full power in 30 seconds, and only 90 seconds is typically required to go from "cold iron" to full power, which is much faster than any steam-power system. CCGT systems may encounter some of the same thermal response restrictions as steam systems but are still expected to provide better operation characteristics, particularly if computerized total ship control systems are employed. The response of the CCGT system to commands for power change depends primarily on the type of control system employed and the type of primary heat source. The use of the bypass system in the CCGT, however, is expected to result in response characteristics that are as quick as open-cycle fuel control systems. Fig. 1.20 shows the fast response to an instantaneous total loss in load. Computerized control systems for CCGT systems which would be similar to those proposed for automated steam plants would have to be developed to allow for rapid transients and simple component efficiency matching.

2.0 Results of Part II - Conceptual Design and Reliability Analysis

The objective of the Part II study was to estimate the heat source performance and weight characteristics to enable selection and conceptual design of a reference closed-cycle gas turbine power conversion system for selected Navy ship propulsion applications. Then, the reliability characteristics for this power conversion system were analyzed and compared to those of a steam propulsion system.

2.1 Heat Source Characteristics and Integration Problems

The state of the art of fossil-fired heat sources suitable for integration with closed-cycle helium gas turbines was reviewed, and candidate heater systems selected for the lightweight ship propulsion application were characterized in terms of performance, size and weight. Heater types investigated include: the conventional combustion chamber; the hot-gas generator/gas-to-gas heater; fluidized beds; configurations with a moving ceramic packing; and compact shell-and-tube designs. The four candidate heater system configurations shown in Fig. 2.1 were selected for parametric performance analyses. Configuration IV was shown to have the highest thermal efficiency (Fig. 2.2) and to be lighter and cost less than Configuration III (Fig. 2.3). Hence, the heater type represented by Configuration IV was selected as the candidate heater, and Fig. 2.4 shows the integration of the heat exchangers and a turbocompressor needed for the conceptual heater design. Combining the heater system design criteria, performance requirements, and size limitations, the cycle definition of the preferred fossil heater was selected, as shown in Fig. 2.5. The estimated overall length of the heater system is 10 meters (33 ft), and the overall diameter is 4.9 meters (16 ft). The estimated specific weight is 1.9 kg/kW (3.15 lbm/shp) without supporting structure; the overall heater system pressure loss is 15 percent, and the heater thermal efficiency is 87.5 percent.

2.2 Selection and Definition of Reference Propulsion System

Utilizing a "Benefit Matrix" screening process, a conceptual high-speed destroyer (HSD) of 3500 to 4000 metric tons displacement, with maximum/cruise speed of 50/20 knots, was found to benefit the most from implementing the CCGT-LWSPS, and therefore was selected as the reference ship type.

For a displacement ship such as an HSD to achieve a maximum speed of 50 knots, a slender hull form is required. As a result, payload volumes are at a premium, making the placement of the high-power propulsion system critical to the ultimate ship utilization. The slender destroyer hull form shown in Fig. 2.6 represents a logical choice for a vessel capable of speeds on the order of

50 knots. The general characteristics of high-speed hulls have been known for some time, but their fine lines restrict engine room sizes and volumes. The engine room dimensions, configurations, and installation requirements based on this figure were used to provide guidelines in Section 2.3 for component sizing and arrangements.

In order to select the reference power conversion system, a benefit matrix was again used to select a 59.7 MW (80,000 SHP) closed-cycle helium turbine incorporating a single free power turbine as the candidate power conversion system to power each of the two shafts on the conceptual high-speed destroyer. An epicyclic gearbox with reversing capability, and a fixed-pitch supercavitating thrustor complete the power train for each shaft. A supercavitating propeller was chosen for the HSD because of the 50-knot maximum speed requirement; the use of a fixed-pitch supercavitating propeller to absorb 80,000 shp appears feasible based on projected 1990 technology. The epicyclic gearbox was chosen because it is lighter and more compact than a single-input offset gearbox.

Interation of the selected propulsion system components yields the schematic flow diagram shown in Fig. 2.7. Each of the two supercavitating propellers and epicyclic gearboxes required for the HSD are driven by a single output shaft from the CCGT power conversion system (two required). This output shaft is mounted on a power turbine which is not mechanically connected to the compressor drive shaft. The compressor drive turbine receives helium gas heated to 816 C (1500 F) by the fossil-fired heater and pressurized to 4.14 megapascals (600 psia) by the two axial compressors. Intercooling is included between the two compressors to reduce the size of the high-pressure compressor and to increase the cycle thermal efficiency. Finally, a precooler is used to reject waste heat and to maintain compressor inlet temperature at 38 C (100 F).

2.3 Conceptual Design of Closed-Cycle Helium Turbine Propulsion System

Conceptual design specifications and drawings were prepared for the 59.7 MW CCGT propulsion system defined above. The conceptual designs of the power conversion system components, including the helium turbomachinery, heat exchangers, ducting, and inventory tanks, were performed in sufficient detail to enable meaningful system layout studies and reliability analyses.

After reviewing the parametric results of Part I - Systems Studies, the reference propulsion system defined in Section 2.2 was refined to identify the component design conditions based on the overall propulsion system requirements. Shown in Table 2.1 are the cycle definitions of the CCGT helium propulsion system. Using this information, the turbomachinery conceptual design (including material selection, component aerodynamic and mechanical designs, engineering drawing, and weight estimates) was prepared by the engine design section at Pratt & Whitney Aircraft Group (a subsidiary of United Technologies Corporation). Both the low-pressure and the high-pressure compressor designs have 12 stages and low exit Mach numbers, so that diffusers downstream of the compressors will not be required.

Based on the preliminary design study, a three-stage compressor drive turbine and a five-stage power turbine were selected. The compressors and turbines described above were integrated into the turbomachinery package which consists of a low-pressure compressor, a high-pressure compressor, a compressor drive turbine, and a power turbine together with cases for bearings and seals and appropriately oriented scrolls at the intake and exhaust. A detailed conceptual design drawing is shown in Fig. 2.8. Because the working fluid is helium gas, internal corrosion problems are not expected. For the most part, external surfaces will be sufficiently cool so that only a high-temperature paint would be necessary as protection from the salt air environment. A thermal blanket on the external cases aft of the thrust mount could be used to prevent excessive heat radiation in the engine room and accidental burns to personnel. The overall size and weights of the selected turbomachinery package are given in Table 2.2.

A representative conceptual design drawing for the three heat exchangers (recuperator, precooler, and intercooler) is shown in Fig. 2.9. The tube-in-shell type of heat exchanger is chosen on the basis of reliability. Based on the cycle definitions (Table 2.1), the dimensions of the turbomachinery package (Fig. 2.8) and the hull shape of the selected reference high-speed destroyer (Fig. 2.6), the maximum effective tube length should be approximately 5.5m (18 ft) for the recuperator, and 1.4 m (4.6 ft) for both the precooler and the intercooler. These requirements on tube length provide a reasonable integration of the three heat exchangers with the turbomachinery to minimize the length of ducting required, the number of bends and the total pressure loss in the ducting. Small-diameter bare tubes were selected for use in the heat exchangers, based on considerations of reliability and maintainability as compared to designs using flat plate-fin construction or finned tubes. Table 2.2 summarizes the overall sizes and weights of the three heat exchangers; a modular approach is used for the construction. The size and weight of the heater systems are also shown in Table 2.2 and are based on the results of Section 2.1 above.

2.4 System Layout and Operational Characteristics

Based on the preliminary propulsion system layout presented above in Section 2.2, a refined version of this layout was developed based on input from J. J..Henry, Inc. For a given displacement, the longer and narrower ships require less horsepower, but necessary stability requirements impose limitations. Hull dimensions (especially length) were chosen as the minimum compatible with the required displacement, powering, and stability. The maximum length of the machinery space is derived from an estimation of flooded length. The basic requirement for a combat vessel over 91 m (300 ft) long is that it should be able to sustain damage over 15 percent of its ength and remain afloat. Based on available information, however, a more restrictive requirement is floodability: the maximum length of the 122 m (400 ft) vessel which can be flooded with the ship remaining afloat is 35 m (115 ft); hence this is the maximum allowable length for the machinery space. The centerline of the propeller shaft, the location and size of the thrust bearings, and the arrangement of the gearbox input/output must also be considered. With all these considerations, the engine room locations and arrangement of the propulsion system machinery in the vessel were chosen and are shown in Fig. 2.6. Engine rooms approximately 14.6 m (48 ft) long were selected and are separated by a 4.9 m (16 ft) cofferdam; thus, the floodable length requirements were satisfied. The engine room arrangements and sizes shown in Fig. 2.6 are consistent with the size and displacement of the high-speed ship. With the engine room sizes having been identified, the preliminary propulsion system layout was made based on the sizes of the major components of the propulsion system; Fig. 2.10 contains a plan view and a side view of this system, and Fig. 2.11 is a perspective view of the system. Based on this layout, the propulsion system (including the power conversion system, the heater system, the transmission gearbox, and the inventory control system) would occupy a space of about 11.4 m (37.5 ft) in width, 12.8 m (42 ft) in length, and 5.3 m (17.5 ft) in height.

The type of control system and primary heat source will directly affect the response of the CCGT to power change commands. Bypass control similar to that used in the High-Temperature Gas-Cooled Reactor (HTGR) can be used to provide any rapid power changes, once the system has attained the normal operating temperatures; these response rates should then equal OCGT characteristics. As can be seen in the potential control schematic shown in Fig. 2.12, the heater would be protected from the high rates of change in pressure since these will occur only in the bypass duct. And should the revised power level be desired for a period of time greater than a few minutes, a more gradual change of working fluid inventory and/or turbine temperature would then be made.

Operating procedures for the CCGT marine propulsion system will not be significantly different from existing land-based CCGT power conversion systems. Even without computerized control systems, the CCGT marine propulsion system should be considerably simpler to operate than a steam turbine propulsion system, although not nearly as simple as an OCGT.

2.5 Reliability Evaluation

One of the major advantages of CCGT systems is their outstanding reliability when compared to that of more conventional power generating equipment, such as OCGT systems. However, a CCGT power conversion system is more complex than an OCGT system, but operating experience with OCGT systems is insufficient for a valid comparison. Therefore, the CCGT reliability was compared with the reliability estimated for conventional steam power conversion systems; the estimates were consistent in both operating/maintenance practices and in a failure rate methodologies. The mission failure rate is the most critical parameter in a reliability estimate. This rate can be estimated using the block approach shown in Fig. 2.13, which represents the interaction of significant components needed to product the desired output. When components are arranged in series as in Fig. 2.13, a failure of any component will result in total system failure; for components in parallel, the failure of one component will not necessarily lead to a system failure. The CCGT system shown in Fig. 2.13 was further subdivided into more than 100 critical components for the analysis.

To estimate the reliability, the LWSP power conversion system was divided into subsystems and components which could be related to existing hardware. The failure rates and/or reliability data for this existing hardware were then adjusted by using engineering judgment to estimate the value of multiplicative correction factors in four separate areas: 1) design difficulty; 2) duty cycle; 3) environmental considerations; and 4) state-of-the-art considerations. As shown in Fig. 2.14, these adjusted component failure rates were then combined to estimate a failure rate for each subsystem, and the subsystem failure rates were then combined to estimate a failure rate for each mission power level.

The results of reliability analysis for the CCGT system and the steam system are shown in Fig. 2.15. When estimates allowing routine repair/replacement practices are considered, the results indicate that the CCGT-LWSPS could be as little as 5.7 percentage points better than a steam system (0.989 vs. 0.932, when alternate configurations are allowed to take 180 minutes for changeover) to as much as 42 percentage points better (0.741 vs. 0.316 when alternate configurations are severely limited). While the absolute values of these reliabilities are not exact, the relative values are consistent and indicative of a reduction in complexity and an increase in reliability with a CCGT-LWSPS. Hence, the use of CCGT-LWSPS is expected to provide a higher mission reliability than a steam power system.

3.0 Results of Part III - Systems Alternatives and Critical Technologies

The objective of the Part III study was to identify and evaluate alternative closed-cycle gas turbine propulsion systems incorporating various electrical and mechanical tranmissions, and to review the critical technologies and development requirements for these propulsion systems. The major test programs, milestones, and cost schedules required to implement the reference CCGT-LWSPS were then identified.

3.1 Electrical Transmission Characteristics and Impact

The weight and size characteristics of advanced electrical rotating machines (generators and motors) for use in electrical transmissions were estimated, and the potential impact of electrical transmissions on the overall feasibility of lightweight propulsion systems was identified. Electrical transmissions offer the potential of high availability and reliability, but the excessive weight and size characteristics of conventional electrical rotating machines have precluded the use of electrical transmissions in the past for Naval ship applications. Superconducting and segmented magnet (SEGMAG) electrical machines, however, are substantially lighter and smaller than conventional machines and may therefore be competitive with mechanical transmissions. Fig. 3.1 is a schematic of a superconducting electrical transmission which joins the prime mover (gas turbine) to the thrustor. From a survey of the literature, the data shown in Fig. 3.2 was obtained for the capacity limits of rotating electrical machines as a function of machine speed. The design points of selected hardware designs are also shown, including the SEGMAG motor and generator, which were developed at Westinghouse with ONR sponsorship. No superconducting rotating electrical machines can be purchased "off the shelf" at this time, and none of the prototype hardware built thus far has a rating as large as the design point levels anticipated for the Naval propulsion application.

Based on data located in the literature survey, the weight, size and performance characteristics of both AC and DC superconducting generators and motors were estimated. Alternatively, the weight, size and performance characteristics of conventional motors and generators were obtained directly from manufacturer's catalogs. The conceptual designs of superconducting equipment, however, generally weigh about one quarter as much as available conventional equipment. The only nonsuperconducting machines with weights comparable to superconducting equipment are the SEGMAG motor and generator. Shown in Fig. 3.3 are the weight characteristics of DC motors, as a function of the full-load torque factor; similar data were also compiled for other superconducting and SEGMAG generators and motors. Fig. 3.4 summarizes the specific weight of advanced electrical transmissions for the selected output capacities applicable to the propulsion systems considered in this study.

Using these weight characteristics, the weights of electric transmissions were estimated for specific ship applications. Table 3.1 shows the weight of the total CCGT propulsion system with a mechanical transmission as compared to propulsion systems with electrical transmissions utilizing superconducting DC machinery or SEGMAG machinery; these comparisons are made for a conventional destroyer with 80,000 shp and also for a high-speed destroyer with 160,000 shp. The bottom line of Table 3.1 is the estimated weight of the total propulsion system. For the conventional destroyer, the propulsion system with the superconducting DC transmission weighs about 15 percent less than the system with the mechanical gearbox, while the propulsion system with the SEGMAG electrical transmission weighs only about 2.5 percent more than the system with the superconducting DC machines. For the high speed destroyer, the system with the mechanical transmission weighs about 7 percent less than either of the systems with electrical transmissions. The payload of a ship with a given total displacement can be determined by subtracting the combined weight of the ship's structure, its propulsion system, and the fuel required for a specfied mission from the total displacement. Table 3.2 shows the weight breakdown of the high-speed destroyer, including payload capabilities with the three types of transmissions and the two different missions.

3.2 Comparative Evaluation of Propulsion System Configurations

The technical merits of alternative propulsion system configurations were compared using the same conceptual-design lightweight propulsion engine but integrated with either mechanical or electrical transmissions. A "Benefit Matrix" which ranks the potential benefits of each combination of engine and transmission was used to select the best propulsion system for the high-speed destroyer and for the conventional destroyer.

Shown in Fig. 3.5 are the eight potential transmission system configurations that were selected for evaluation for the two ship types. For the mechanical transmissions, both epicyclic and offset reduction gearboxes were considered. For the electrical transmissions, six configurations were considered: two utilizing SEGMAG DC machines, two using superconducting AC machines, and two using superconducting DC machines. The main factor considered in screening the transmission system alternatives shown in Fig. 3.5 was the compatibility of the thruster and transmission system with the reference propulsion engine. The second factor was the limitation projected for 1990 on component capabilities. Hybrid systems (which combine mechanical gearboxes and electrical machines) were not considered. Based on these criteria, twelve candidate propulsion system alternatives (designated as C1 to C8 in Fig. 3.5 for the high-speed destroyer, and as C9 to C12 for the conventional destroyer) were selected. The overall efficiency, size, specific weight, and specific capital costs for each of the twelve candidate propulsion system configurations were characterized.

In order to systematically compare the technical merit of the candidate propulsion systems, ten evaluation criteria, each carrying a different weighing factor shown in Table 3.3 were established to provide a basis for rating the candidate systems, as shown in Table 3.4. The weighing factors which range from 1 to 5 (with 5 being the highest) indicate the relative importance of each evaluation criterion in the system evaluation. Then, the ratings of each of the candidate systems were tabulated in terms of the ten criteria. Based on the weighing factors and the individual rating for each propulsion system configuration, the total rating is then calculated by summing the product of the weighing factor and the corresponding rating for each system. The results are given in the bottom line of Table 3.4. For the high-speed destroyer, the C1 configuration (which has a mechanical transmission with an epicyclic reduction gearbox) is the most desirable, scoring 179 points out of a possible 200, which is closely followed by the C2 configuration (with the SEGMAG system) scoring 176/200. For the conventional destroyer in the 1990's, an electrical-drive propulsion system which consists of the reference propulsion engine driving two SEGMAG DC generator-motor sets would be preferable.

3.3 Identification of Critical Component Technologies

The current technological barriers and constraints of the selected propulsion systems were identified by reviewing recent advancements in the applicable technologies for each of the crucial components. Then major test programs, milestones, and costs to demonstrate the selected closed-cycle gas turbine propulsion system were delineated.

The current status of OCGT technology was assessed first, because much of the OCGT expertise is directly transferable to the CCGT field. The critical technology for open-cycle gas turbines is cooling the hot-section components. Because ceramic hot-section hardware will probably not be in production by 1990, attention must be directed toward metals (superalloys) to assure acceptable durability for these high-cost parts while not drastically penalizing performance. Similarly, the most critical technology area for closed-cycle gas turbine systems is that of the maximum cycle temperature. In contrast to the OCGT hot section, the metal temperatures in the closed-cycle heater will always be higher than the working gas temperature. The progression of turbine inlet temperatures projected for CCGT systems was shown earlier in Fig. 1.7. For the 1990 time period, this temperature is limited to 816 C in this study by the material characteristics at the metal temperatures required in the heater portion of the system; the maximum temperature in the closed-cycle loop occurs at the heater outlet where the recirculating gas is normally brought to a temperature limited by the materials in the heater itself. When ceramics become available (probably after 1990), the allowable turbine inlet temperature is expected to increase dramatically by 200 C to approximately 1000 C.

The technical barriers and constraints of the selected CCGT propulsion system, summarized in Table 3.5, are identified in three technology areas: turbomachinery, heat exchangers, and the overall system. Methods to remove these technological barriers were identified: both a preferred barrier removal method and alternative methods using substitutes to provide a demonstration system. Main-shaft thrust bearings, high-speed thrustors, and electrical and mechanical transmissions all require development work to verify operation at power levels beyond those of current technology systems.

Many of the components in the selected reference CCGT propulsion system will require additional testing and development during the next ten years to allow their utilization in Navy ships by 1990. The subjects and requirements of these tests are summarized in seven technology areas in Table 3.6. Further, because the selected lightweight ship propulsion system will probably not be installed on a ship until its design has achieved a substantial level of operational success, certain modifications will have to be made to the system for demonstration testing to simulate the installed environment. For example, a method for absorbing the output shaft power would have to be substituted for the propeller. Other modifications would be prudent for testing or demonstrating the operations of a full-size system, while still other modifications might allow more cost-effective testing and demonstration. These modifications are summarized in Table 3.7.

For the CCGT propulsion system to be utilized by 1990 in Naval ships, a large research and development program must be started in the near future. The duration and cost of this program are estimated at between seven to ten years and \$340 million, but even these figures may be near the minimum levels to meet the 1990 goals. The schedule in a success-oriented program and the projected cost for these development items are delineated in the report, and the annual program expenditures are shown in Fig. 3.6.

Table 1.1

LWSPS General Requirements and Constraints

- 1985-1990 technologies - fossil or nuclear powered
- Low SFC (<0.4 lb/shp-hr) or high thermal efficiency (>38%)
- Low specific weight (lb/shp) and volume (ft^3/shp)
- Compatible maximum cycle temperature
- Heat rejection through fresh/salt water loops
- 40,000-300,000 shp range installed
- Four or less thrustors driven by six or less engines
- High system reliability, maintainability, and Low vulnerability
- Reasonable system lifetime (>30,000 hr) and TBO
- Low initial and operating costs

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TABLE 1.2

LWSPS Component Capability Limitations

Component	Unit capacity, shp	No. units	Configuration
Gas turbine			
OCGT	20,000-50,000	≤ 4 + lift	1 power turbine
CCGT	40,000-300,000	≤ 4 + lift	0,1, or 2 power turbines
Gear box			
Offset	<150,000		1 or 2 stages
Epicyclic	<100,000		1 or 2 stages
Bevel	<60,000		1 stage
Thrustor			
Fixed pitch	20-100,000	≤ 6	Sub. (F) and supercavitating ($\bar{F}$)
C.R.P.	20-60,000	≤ 6	Sub. (R) and supercavitating ($\bar{R}$)
Water jet	20-50,000	≤ 6	W

TABLE 1.3

Selected Baseline Engine Characteristics

Open–cycle gas turbine

Output power (shp)	sfc (lb/shp–hr)	TIT (F)	Specific weight (lb/shp)	Pressure ratio	Output shaft speed (rpm)
20,000	0.395	2,400	1.71	20	4,800
30,000	0.390	2,450	1.32	22	4,200
40,000	0.385	2,500	1.10	25	3,800
50,000	0.380	2,550	0.96	28	3,600

Closed–cycle gas turbine

Output (power) (shp)	sfc (lb/shp–hr)	Specific weight (lb/shp)	Max. pressure (psia)	Power turbine (rpm)
40,000		2.45	580	5,400
60,000	0.38 (1500 F TIT)	2.09	620	5,200
80,000		1.87	650	4,800
100,000	0.36 (1600 F TIT)	1.72	680	4,600
120,000	0.35 (1700 F TIT)	1.66	720	4,400
150,000		1.60	760	4,000
160,000		1.58	780	4,000
200,000		1.51	840	3,800

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TABLE 1.4

ESTIMATED PROPULSION SYSTEM EQUIPMENT CAPITAL COSTS AND FUEL COSTS

Capital Costs Presented in Dollars per Installed Power, $/shp

Fuel Costs Presented in Dollars per shp for 100 Hours of Operation

Ship Type	Destroyer		H.S. Destroyer		HPS	
Installed Power - shp	80,000		160,000		200,000	
Displacement - long tons	4250		4000		3000	
Propulsion Systems	OCGT	CCGT	OCGT	CCGT	OCGT	CCGT
Power Conversion system	81.00	118.50	63.50	84.00	63.50	115.00
Gearbox	21.33	15.84	21.57	10.46	20.85	10.46
Shafting	6.90	6.90	1.98	1.98	1.70	1.70
Thrustors	10.8	10.8	3.00	3.00	2.31	2.31
Bed Plate	1.14	1.31	0.73	1.09	0.81	1.27
Intake and Uptake	4.50	*	4.50	*	3.00	*
Heater	NA	*	NA	*	NA	*
Miscellaneous	35.52	25.00	23.16	12.70	20.40	12.80
Total Capital Cost	161.19	178.35#	118.44	113.23#	112.57	143.54#
Fuel Cost+	0.51	0.38	0.68	0.57	1.13	1.02

* To be investigated in Phase II.1 of Part II study
\# Does not include heater
\+ Based on Diesel Fuel Marine

TABLE 2.1

CYCLE DEFINITIONS OF HELIUM CCGT PROPULSION SYSTEM

Intercooled Recuperator Cycle	
Turbine Inlet Temperature, C	815.56
Compressor Inlet Temperature, C	37.78
Turbine Inlet Pressure, bar	44.83
Compression Ratio	3.0
Recuperator Effectiveness, %	90.0
Cycle Pressure Loss, %	13.5
Heater, %	3.0
Recuperator, %	4.0
Intercooler, %	1.5
Precooler, %	3.0
Ducting, %	2.0
Output power, MW	59.7 (80,000 shp)

TABLE 2.2

SUMMARY OF LIGHTWEIGHT POWER CONVERSION SYSTEM
COMPONENT DIMENSIONS AND WEIGHT

Components	Length (m)	Diameter (m)	Weight (kg) Dry	Weight (kg) Wet
A. Power Conversion System				
Turbomachinery	6.70	1.52	9,545	9,559
Regenerator	7.62	2.36	44,040	44,128
Precooler	3.16	1.60	6,020	9,366
Intercooler	3.16	1.43	5,430	7,897
Inventory Vessels (6 Units)	6.60	0.67	6,294	6,294
Ducting	9.45	30 ~ 0.4	729	731
Total			72,058 (=1.98 lb/shp)	77,975 (=2.14 lb/shp)
B. Heater Systems				
Helium Heater	6.55 x 5.33	2.74	40,130	
Turbomachinery	1.22	1.22	3,022	
Air Recuperator	1.98	1.37	2,596	
Combustor & Mixer	1.98 x 1.52	0.76	682	
Ducting	6.10	3.66	435	
Intake (duct, silencer & demister)	12.20	3.66	18,727	
Uptake (duct, silencer & educator)	12.20	3.05	48,636	
Total			114,464 (=3.15 lb/shp)	

TABLE 3.1

PROPULSION SYSTEM WEIGHTS FOR CONVENTIONAL AND HIGH-SPEED DESTROYER INSTALLATIONS

	Conventional Destroyer CCGT	High Speed Destroyer CCGT
Speed, Max./Cruise, m/s (knots)	18/10 (35/20)	26/10 (50/20)
Displacement, m ton (long tons)	7926 (7800)	3556 (3500)
Installed Power, MW (shp)	59.7 (80,000)	119.4 (160,000)
Displacement/Power, kg/kW (lbm/shp)	132.3 (218)	29.8 (49)
Total Structure/Displacement	0.45	0.44
Structure Sp. Wt., kg/kW (lbm/shp)	59.8 (98.3)	13.1 (21.6)

Number of Thrustors	2			2		
Thrustor Speed, RPM	230			580		
Type of Thrustor	CRP	FP	FP	FP	FP	FP
Type of Transmission	Mech	Electr. S/C DC	Electr. SEGMAG	Mech	Electr. S/C DC	Electr. SEGMAG
Propulsion System Sp. Wt., kg/kW (lbm/shp)						
"Wet" Power Conversion System	1.30 (2.14)	1.30 (2.14)	1.30 (2.14)	1.30 (2.14)	1.30 (2.14)	1.30 (2.14)
Bed Plate	.87 (1.43)	.58 (0.95)	.58 (0.95)	.87 (1.43)	.58 (0.95)	.58 (0.95)
Transmission	2.24 (3.69)	2.07 (3.40)	2.25 (3.70)	.53 (0.87)	1.34 (2.20)	1.36 (2.24)
Shafting - Inboard	.58 (0.95)	.19 (0.32)	.19 (0.32)	.21 (0.35)	.12 (0.19)	.12 (0.19)
- Outboard	.74 (1.22)	.74 (1.22)	.74 (1.22)	.30 (0.49)	.26 (0.42)	.26 (0.42)
Thrustor	.94 (1.54)	.49 (0.80)	.49 (0.80)	.09 (0.14)	.09 (0.14)	.09 (0.14)
Subtotal	6.67 (10.97)	5.37 (8.83)	5.55 (9.13)	3.30 (5.42)	3.69 (6.04)	3.71 (6.08)
Others	2.00 (3.29)	1.61 (2.65)	1.67 (2.74)	.99 (1.63)	1.10 (1.81)	1.11 (1.82)
Heater Systems	2.64 (4.35)	2.64 (4.35)	2.64 (4.35)	2.64 (4.35)	2.64 (4.35)	2.64 (4.35)
Total Weight	11.31 (18.61)	9.62 (15.83)	9.86 (16.22)	6.93 (11.40)	7.43 (12.20)	7.46 (12.25)

TABLE 3.2

WEIGHT BREAKDOWN OF HIGH-SPEED DESTROYER
given in metric tons (long tons)

Mission	Cruise 3000 Nautical Miles at 20 Knots			100-Hr Duty Cycle		
Types of Transmission	Mech.	S/C DC Electr.	SEGMAG DC Electr.	Mech.	S/C DC Electr.	SEGMAG DC Electr.
Total Displacement	3556 (3500)	3556 (3500)	3556 (3500)	3556 (3500)	3556 (3500)	3556 (3500)
Structure	1565 (1540)	1565 (1540)	1565 (1540)	1565 (1540)	1565 (1540)	1565 (1540)
Propulsion System	761 (749)	819 (806)	822 (809)	761 (749)	819 (806)	822 (809)
Amount of Fuel for Mission	551 (542)	464 (457)	464 (457)	876 (862)	843 (830)	843 (830)
Payload	680 (669)	709 (697)	705 (694)	355 (349)	330 (324)	326 (321)
Payload as % of Total Displacement	19.1	19.9	19.8	10.0	9.3	9.2

TABLE 3.3

Evaluation Criteria for LWSPS Alternatives

Criteria	Weighing Factor (1 to 5)
1. Lightweight	5
2. Compactness	5
3. Fuel efficiency	5
4. Reliability and maintainability	5
5. Ship layout	4
6. Auxiliary requirements	4
7. Control & response	4
8. Operational flexibility	3
9. Projected capital cost	3
10. Development requirements	2

TABLE 3.4

SELECTION OF REFERENCE LIGHTWEIGHT PROPULSION SYSTEMS

Evaluating Criteria	Weighting Factor 1 to 5	Rating of Alternative Propulsion System Configurations											
		High-Speed Destroyers								Conventional Destroyers			
		2-Engines, 2-Shafts				2-Engines, 4-Shafts				1-Engine, 2-Shafts			
		C1 EPIC	C2 SEG MAG	C3 S/C AC	C4 S/C DC	C5 OFF SET	C6 SEG MAG	C7 S/C AC	C8 S/C DC	C9 OFF SET	C10 SEG MAG	C11 S/C AC	C12 S/C DC
1. Lightweight	5	5	4	5	5	3	4	5	5	3	4	5	5
2. Compactness	5	5	5	4	4	3	4	3	3	4	5	4	4
3. Fuel Efficiency	5	4	5	5	5	4	5	5	5	4	5	5	5
4. Reliability & Maintainability	5	5	4	3	3	5	4	3	3	5	4	3	3
5. Ship Layout	4	4	5	5	5	2	3	3	3	4	5	5	5
6. Auxiliary Requirement	4	5	4	2	3	5	4	2	3	5	4	2	3
7. Control & Response	4	4	5	4	4	4	5	4	4	3	5	4	4
8. Operational Flexibility	3	3	4	4	4	4	5	5	5	2	5	5	5
9. Projected Capital Cost	3	5	4	4	4	5	4	4	4	5	3	4	4
10. Development Requirement	2	4	3	2	3	4	3	2	3	4	3	2	3
TOTAL RATING		179	176	157	163	151	166	147	153	157	176	160	166

Table 3.5

Technological Barriers and Constraints of Closed-Cycle Lightweight Ship Propulsion Systems

Turbomachinery Technology

- Helium Flow Dynamics
- Transient and Dynamic Operational Characteristics
- Sealing and Bearing Designs
- Critical Speeds
- Ducting and Inlet/Outlet Pressure Loss

Heat Exchanger Technology

- Cycle Temperature Limitations
- Heater Operational Characteristics
- Fabrication Techniques and Costs
- Maintenance Practices

Overall System Technology

- Control System
- Electric Transmission Weight, Complexity, Cost
- Supercavitating Propeller Performance and Capacity
- Containment of Large Turbomachinery

Table 3.6

Testing and Development Requirements

Turbomachinery Technology and Design Verification

- Blade Shapes
- Boundary Layer Characteristics
- Stall Characteristics
- Localized Heat Transfer Coefficients
- Operation of Turbomachine Components
- Integrated Turbomachine Operation

Heat Exchanger and Heater Technology and Design Verification

- Corrosion of Superalloys
- Helium Environment Effects on Material Properties
- Ceramic Corrosion Resistance
- Heat Exchanger Transient Thermal Stresses
- Operational Characteristics and Design Verification

Pressure Loss Characteristics

- Inlet/Outlet and Transition Losses
- Ducting and Valve Losses
- Heat Exchanger Losses

Control and Transient Operation Characteristics

- Interaction of Sub-Scale Model Components
- Turbomachine Transient Limitations
- Characteristics of Sub-Scale Heater
- Part-Load Limitations

Sealing and Bearings

- Full Size Rig Performance Characteristics

Supercavitating Propeller

- Continue Development
- Improve Efficiency
- Increase Output

Mechanical and Electric Transmissions

- Continue Testing and Development of Large Epicyclic Designs
- Continue Development of SEGMAG or Superconducting Designs
- Resolve AC/DC Tradeoffs

Table 3.7

System Modifications for Demonstration Testing

For Full-Scale As Designed System Demonstration

- Add Power Absorption System for Land-Based Demonstration
- Install for Power On One-Shaft of Existing Cruiser, Battleship, or Carrier
- Utilize Nonintercooled Cycle for Simplicity
- Set Compressor Inlet Temperature and/or Pressures to Convenient Level
- Simulation of Shock Testing

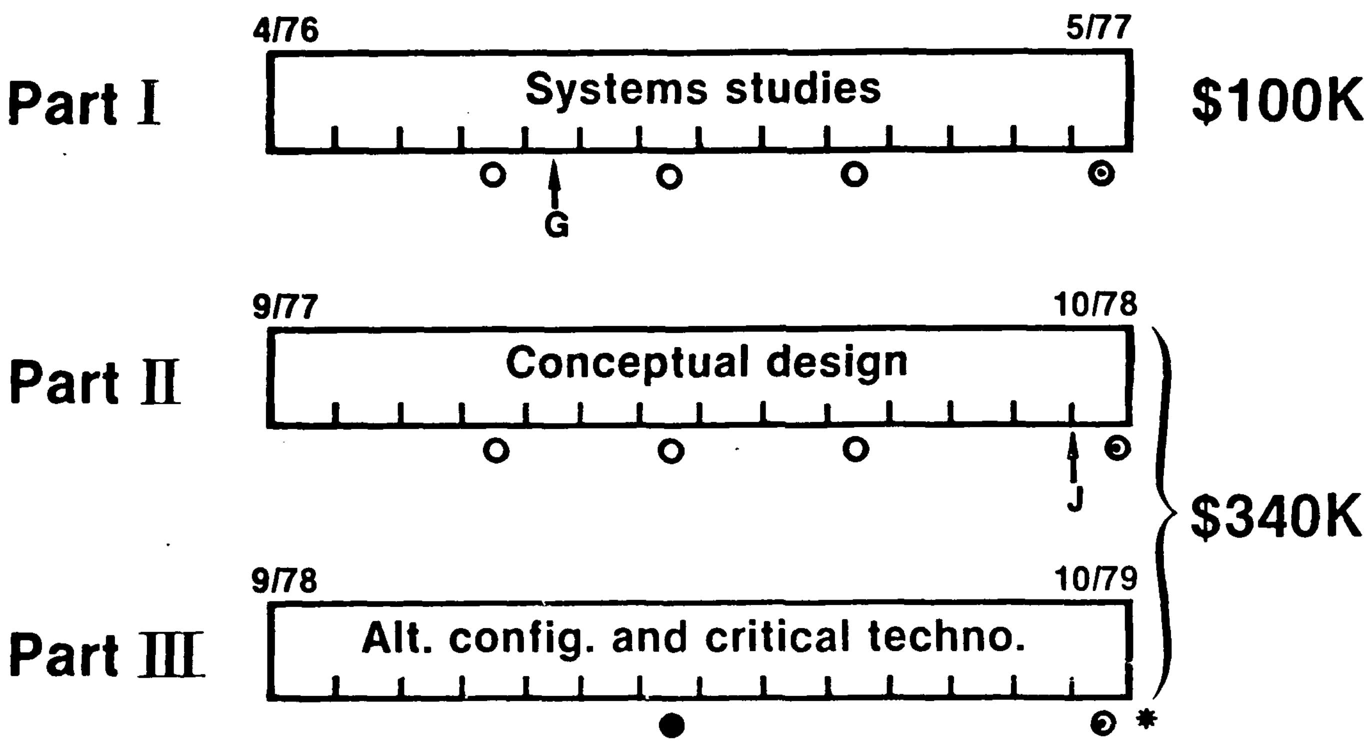
For Sub-Scale System Demonstration

- Demonstrate in Existing Land-Based Facility
- Install in Current Destroyer for Partial Power
- Simulate Heat Exchanger Effects in Tullahoma-Type Facility
- Set Compressor Inlet Pressures and/or Temperatures to Convenient Level

Cost-Saving Demonstrations

- Reduced Maximum Temperature Capability
- Reduced Regenerator Effectiveness
- Revised Regenerator Tube Size
- Modify Existing Boiler to Provide Heater Function
- Utilize Simpler Nonintercooled Cycle
- Utilize Revised Power Turbine Design (Single Shaft)
- Utilize Air for Working Gas (Reduced Output, Existing Turbomachinery)

LWSPS Program Schedule & Costs



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Characterization of Selected Naval Ships

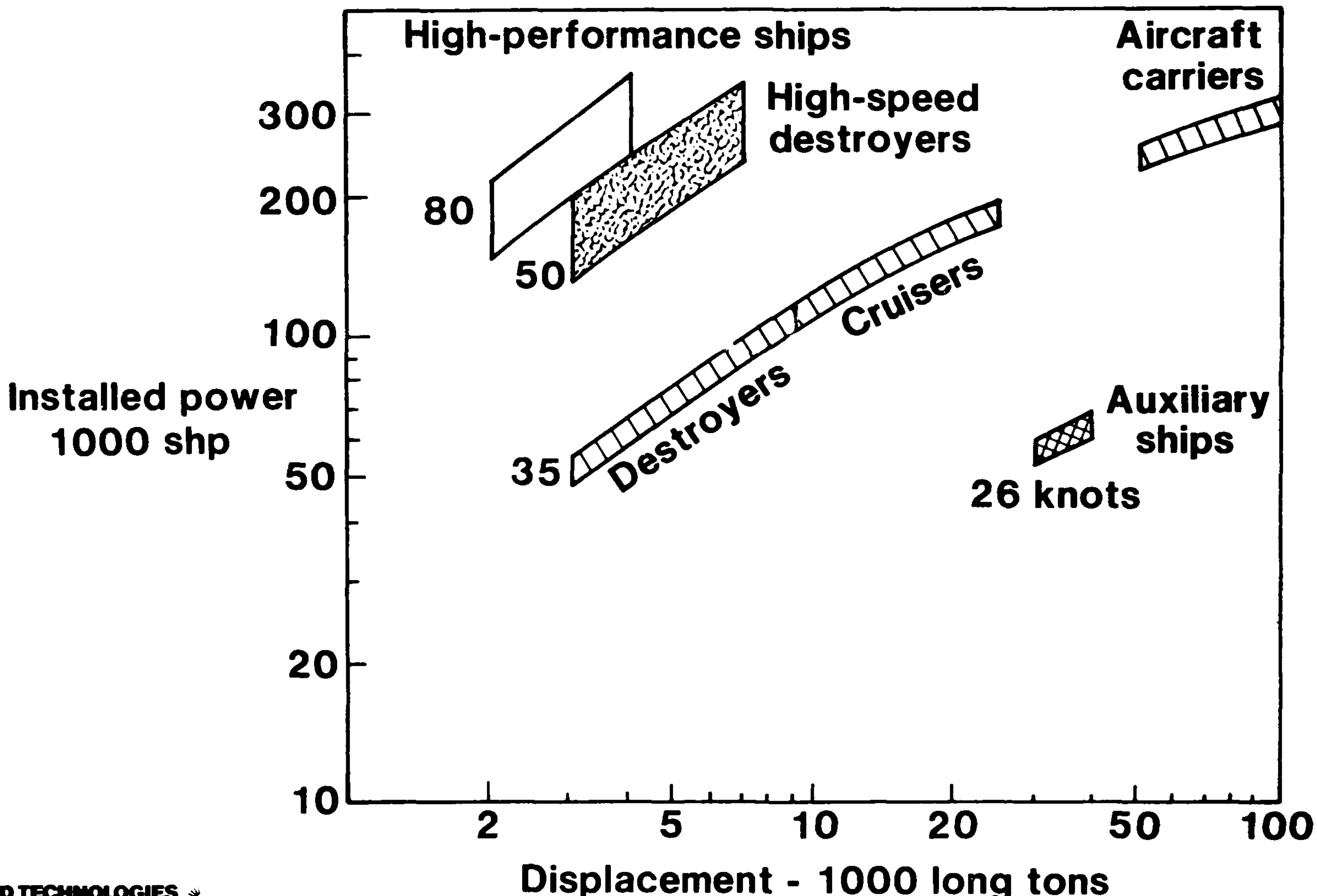

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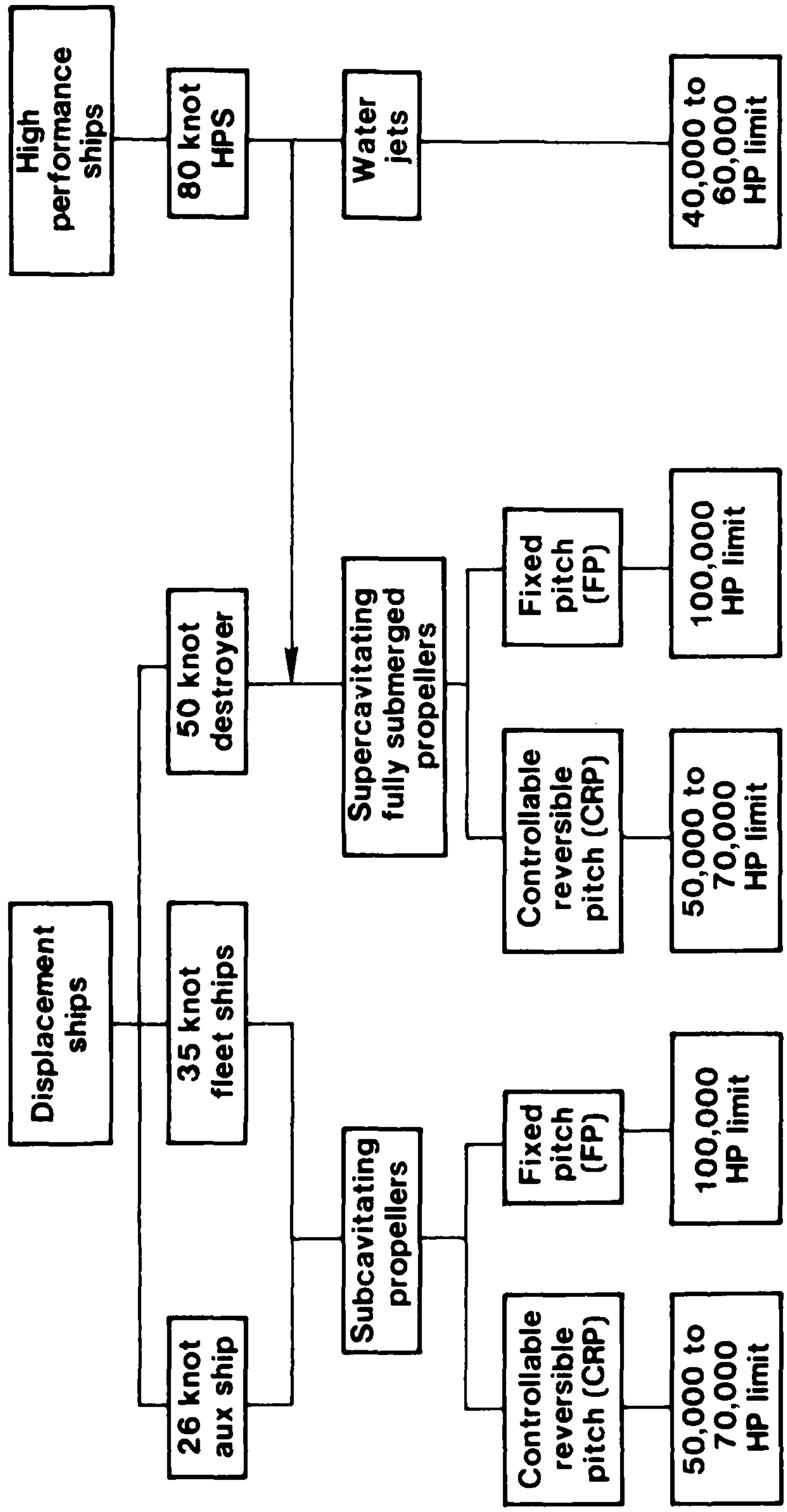
Fig. 1.1

Fig. 1.2

Thrustors Selected



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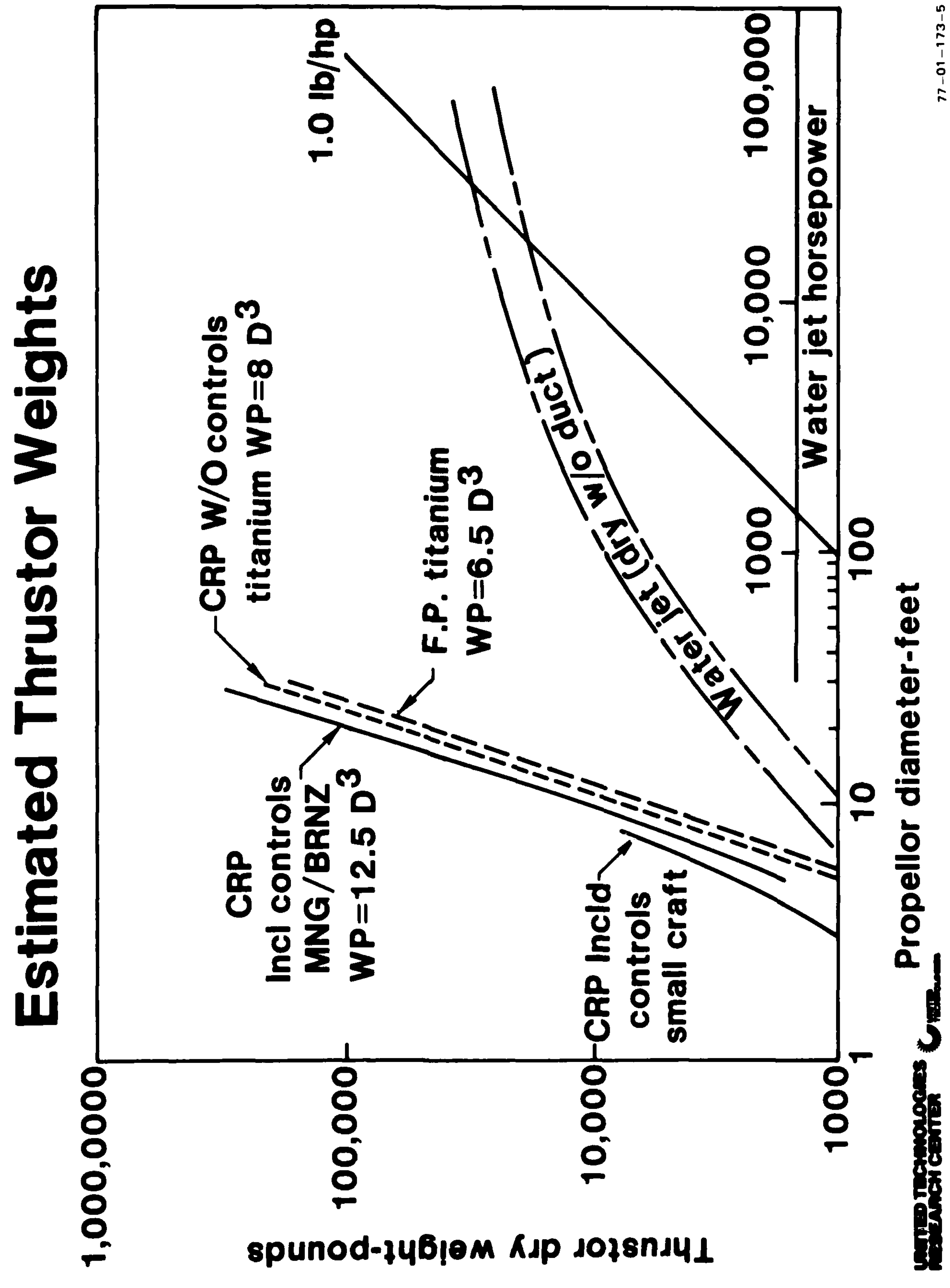
Estimated Thrustor Weights
Thrustor dry weight-pounds
1,000,0000
100,000
10,000
1000
1
10
100
1000
10,000
100,000
Propellor diameter-feet
Water jet horsepower
1.0 lb/hp
CRP W/O controls titanium WP=8 D3
F.P. titanium WP=6.5 D3
CRP Incl controls MNG/BRNZ WP=12.5 D3
CRP Incld controls small craft
Water jet (dry w/o duct)
77-01-173-5
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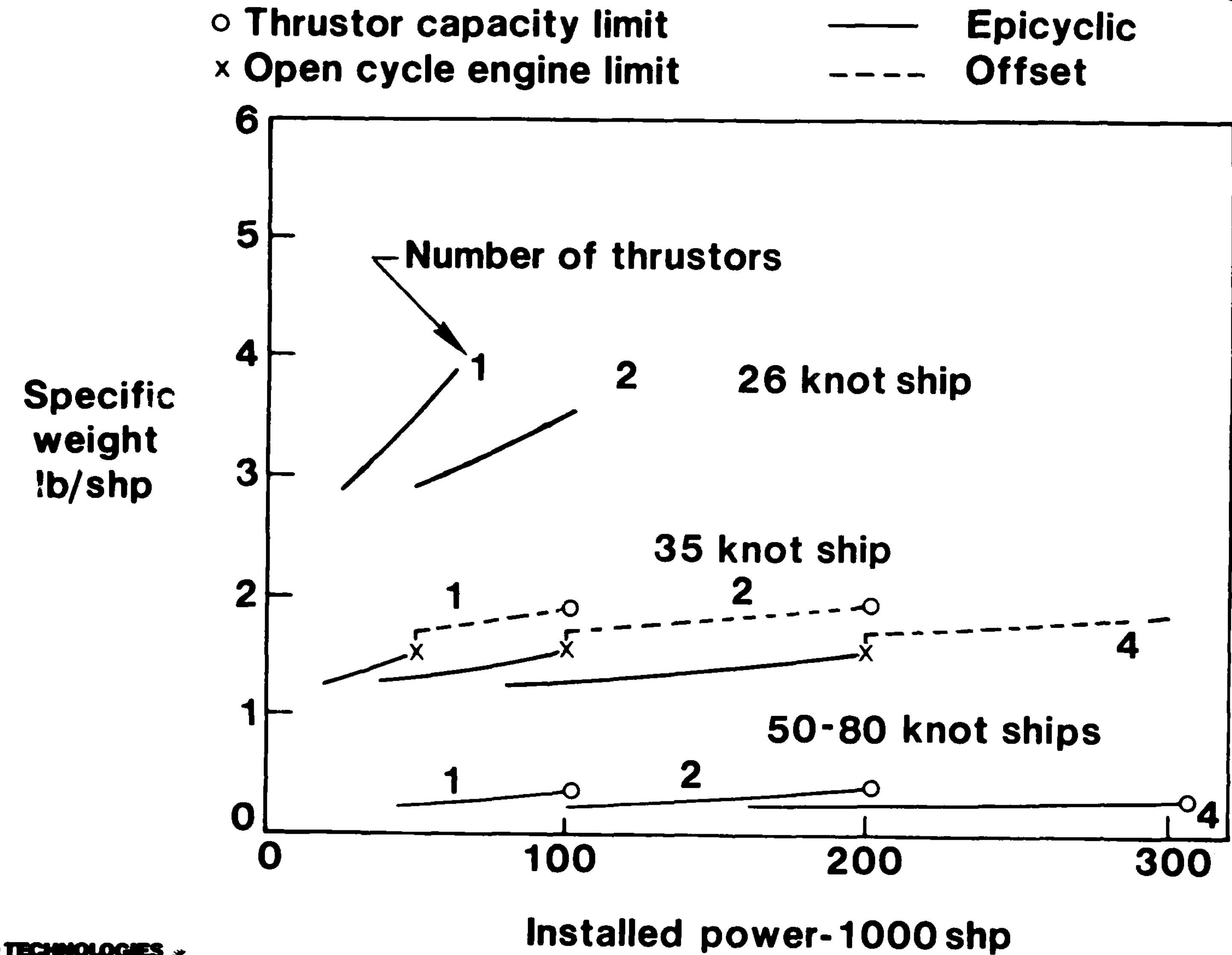
Estimated Minimum Gearbox Specific Weight



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Estimated Shaft Specific Weight

Diameter ratio: 0.65
Stress: 10000 psi, conventional
12000 psi, 50 knot

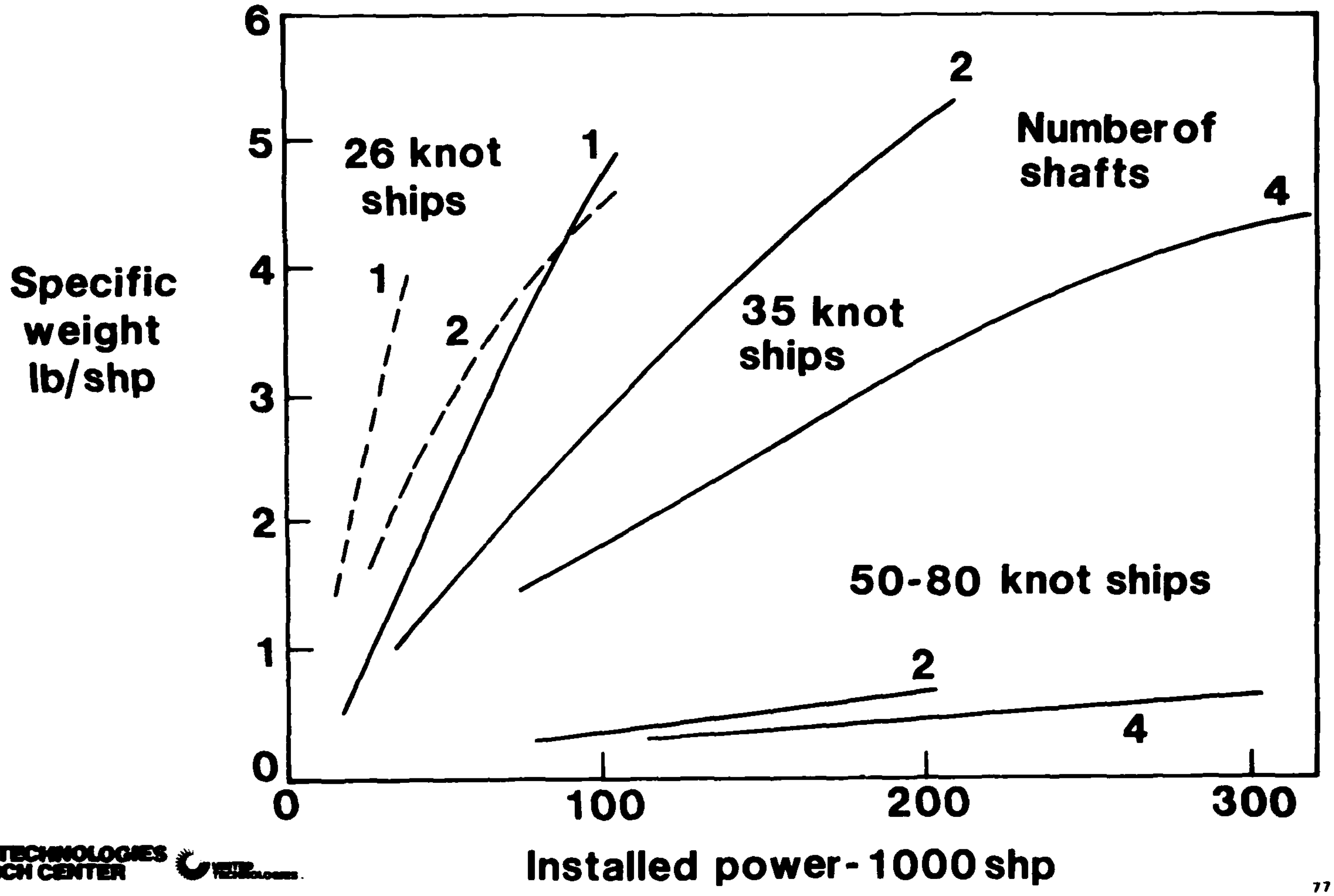

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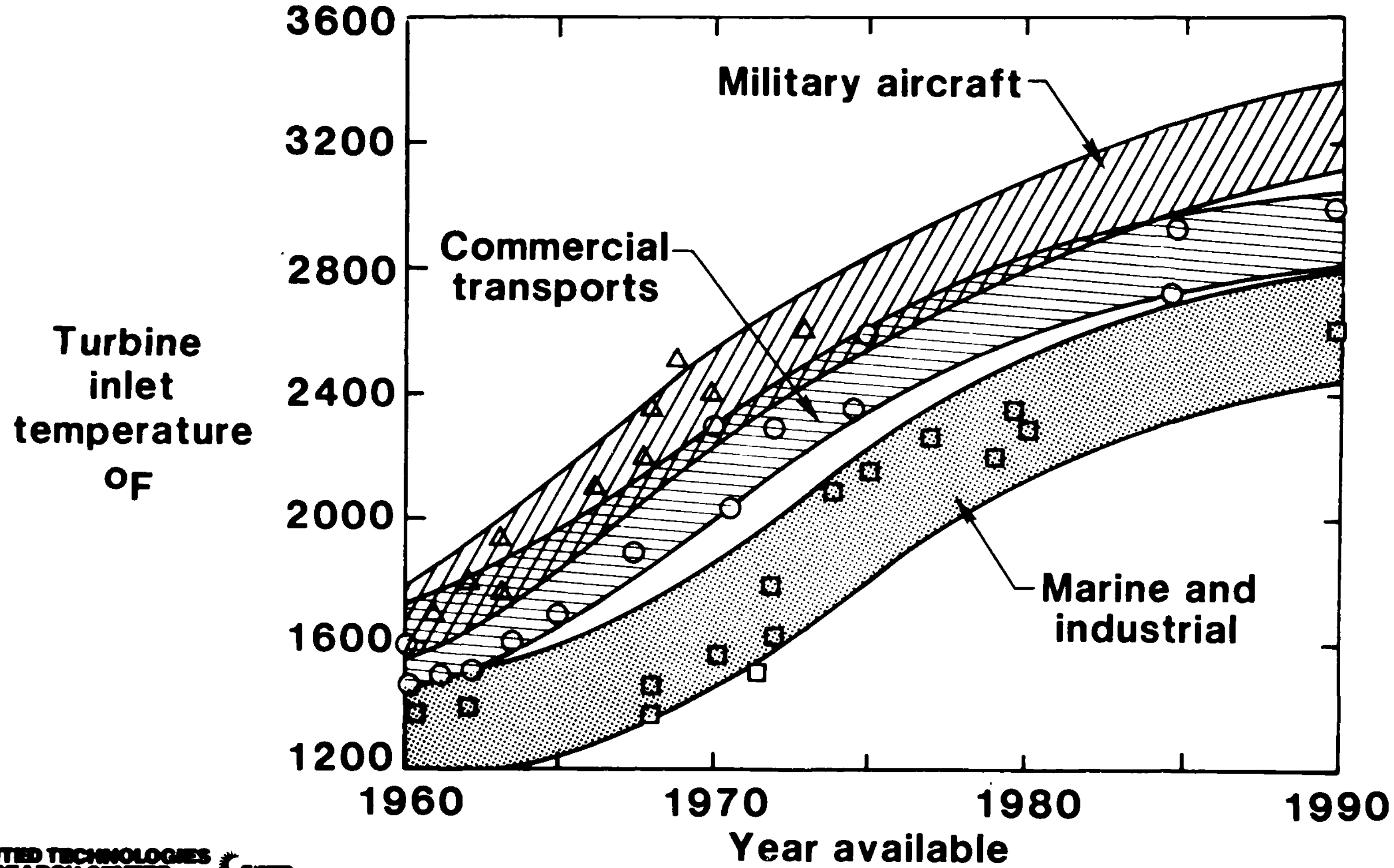
Fig. 1.5

Estimated Progression of Turbine Inlet Temperature



76-09 244-4

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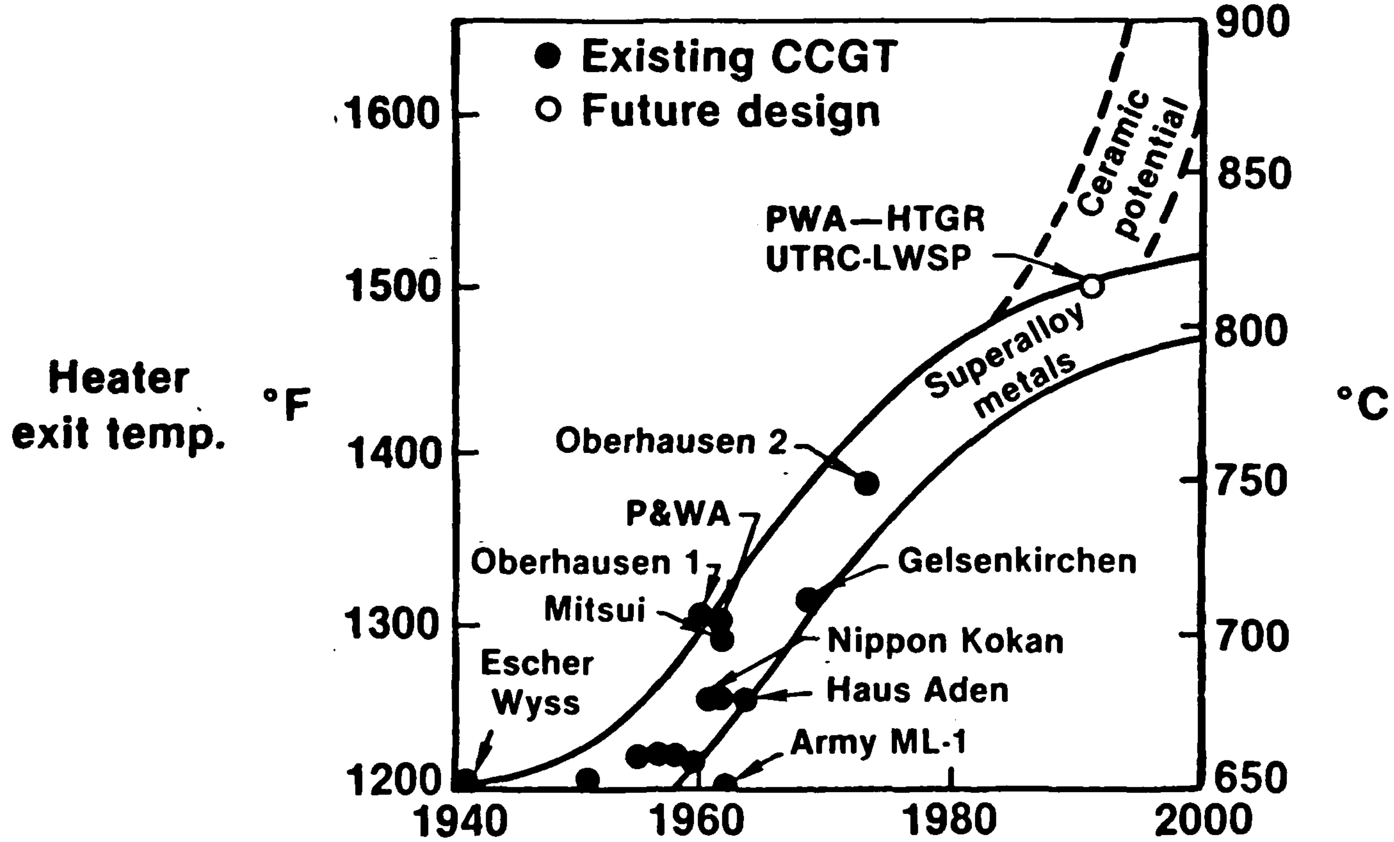
Projected Closed-Cycle Gas Turbine Maximum Temperature Progression



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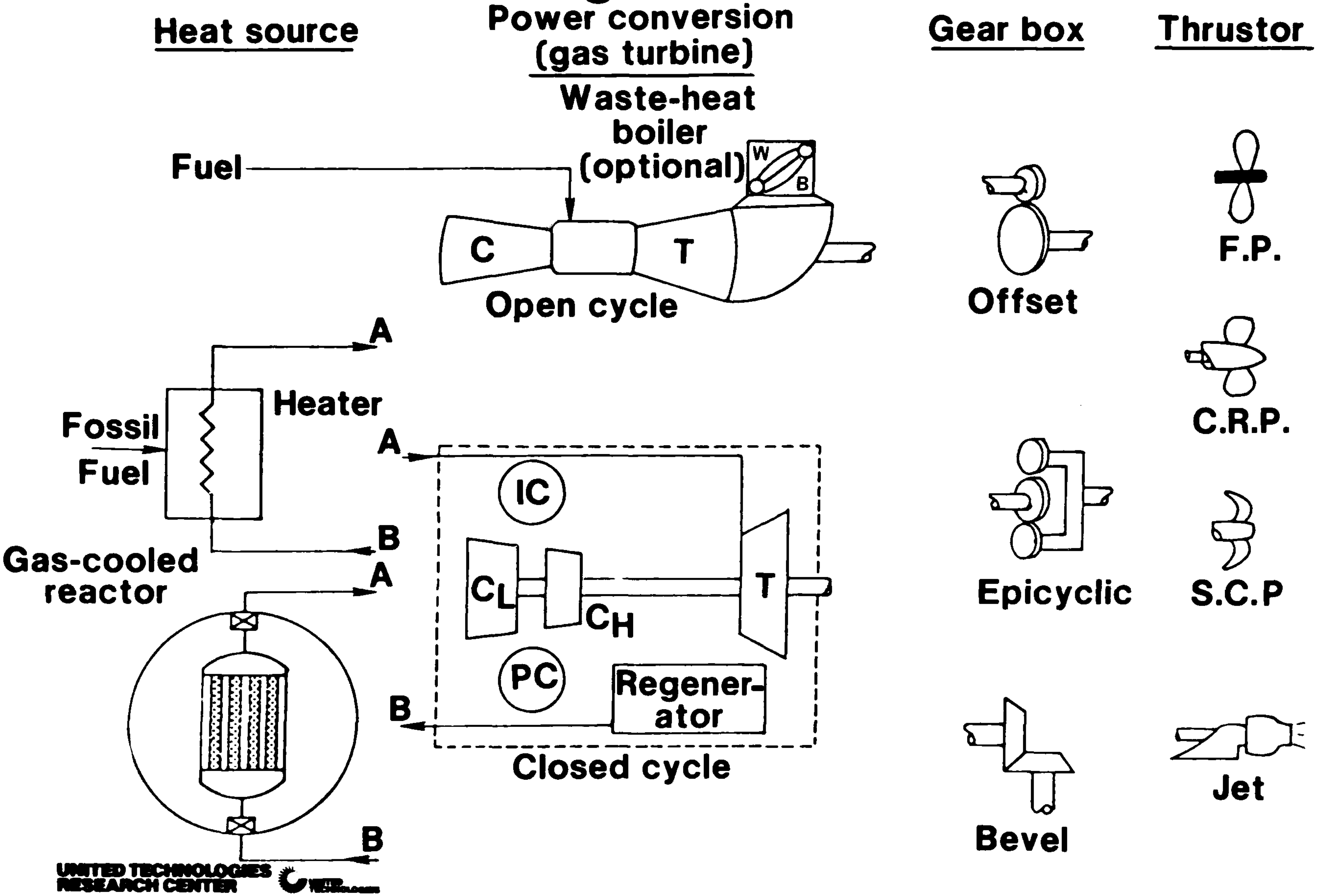
LWSPS Configuration Alternatives



Basic Arrangements and Selection Matrix for Lightweight Ship Propulsion Systems

Engine limitations   Thrustor limitation   • Gear box limitation

√ Compatible/less attractive   F, $\bar{F}$, R, $\bar{R}$, W Applicable thrusters

Basic arrangements	Shp	40K		60K		80K		120K		160K		200K		240K		300K	
	Cycle	O	C	O	C	O	C	O	C	O	C	O	C	O	C	O	C
A 11θ &E	1unit		√		√		√			•	•	•	•	•	•	•	•
	2						√		√		√		$\bar{F}$				
	4										√		√		√		√
B 11θ &E	1	FR	FR		FR		F			•	•	•	•	•	•	•	•
	2	FR		FR		FR	FR		FR		F$\bar{F}$		√				
	4					√		FR		F$\bar{F}$ R$\bar{R}$W	√	FR W	√		√		√
C 12θ	1	FR	√		FR		FR		FR	•	•	•	•	•	•	•	•
	2					FR	√		FR		F$\bar{F}$ R$\bar{R}$W		FR W		F$\bar{F}$ R$\bar{R}$		F$\bar{F}$
	4																
D 11θ & E	1		√		√		FR		FR		F$\bar{F}$		$\bar{F}$				
	2						√		√		√		FR W		F$\bar{F}$ R$\bar{R}$		F$\bar{F}$
	4																
E 21θ	1	FR		FR		F	√			•	•	•	•	•	•	•	•
	2					FR		FR		F$\bar{F}$	√	$\bar{F}$	√				
	4																

Closed-Cycle Helium Gas Turbine Performance

Turbine inlet temperature 1500°F

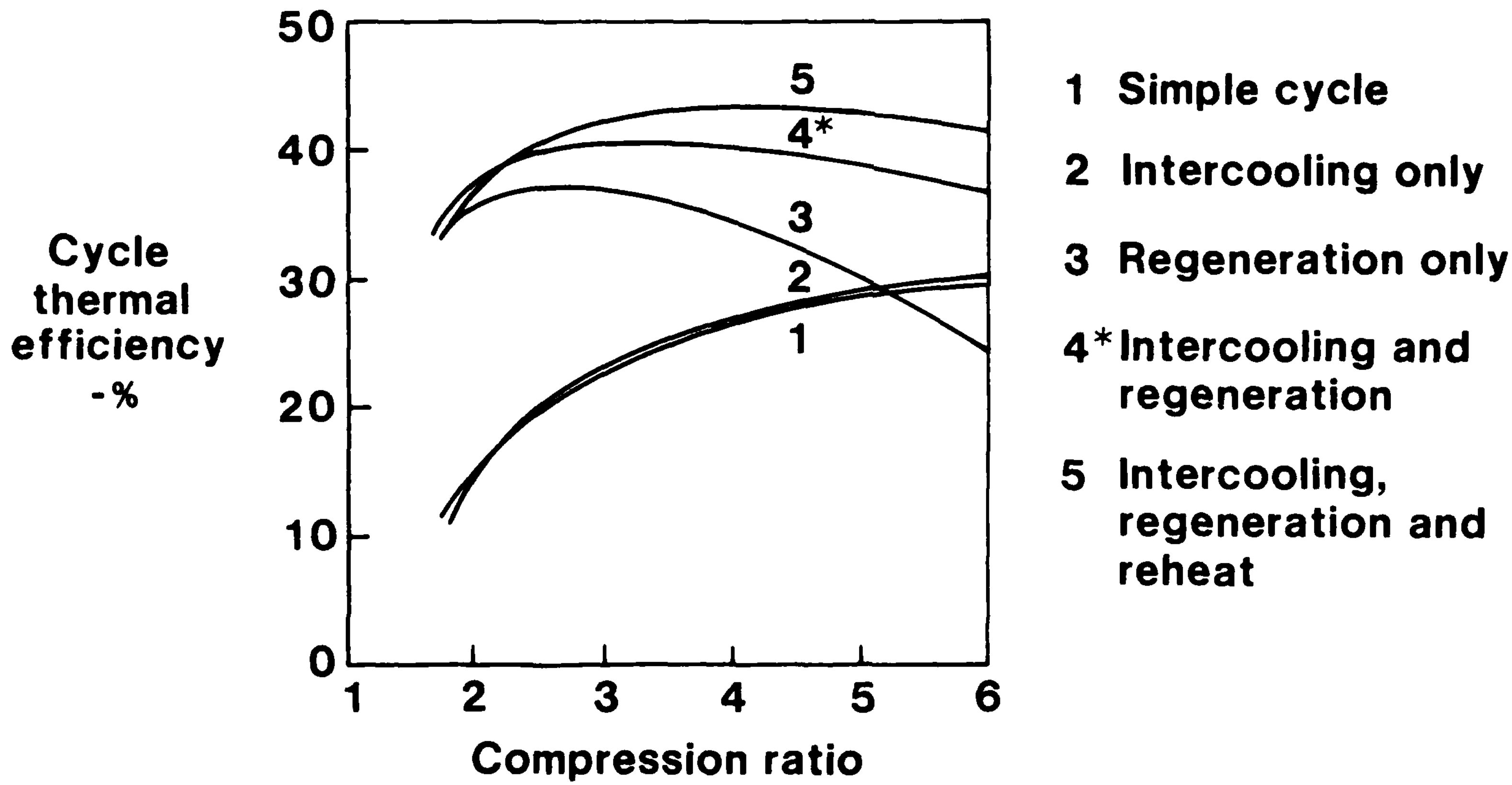


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Fig. 1.10

Estimated Baseline CCGT Power Conversion Systems Installed Weight

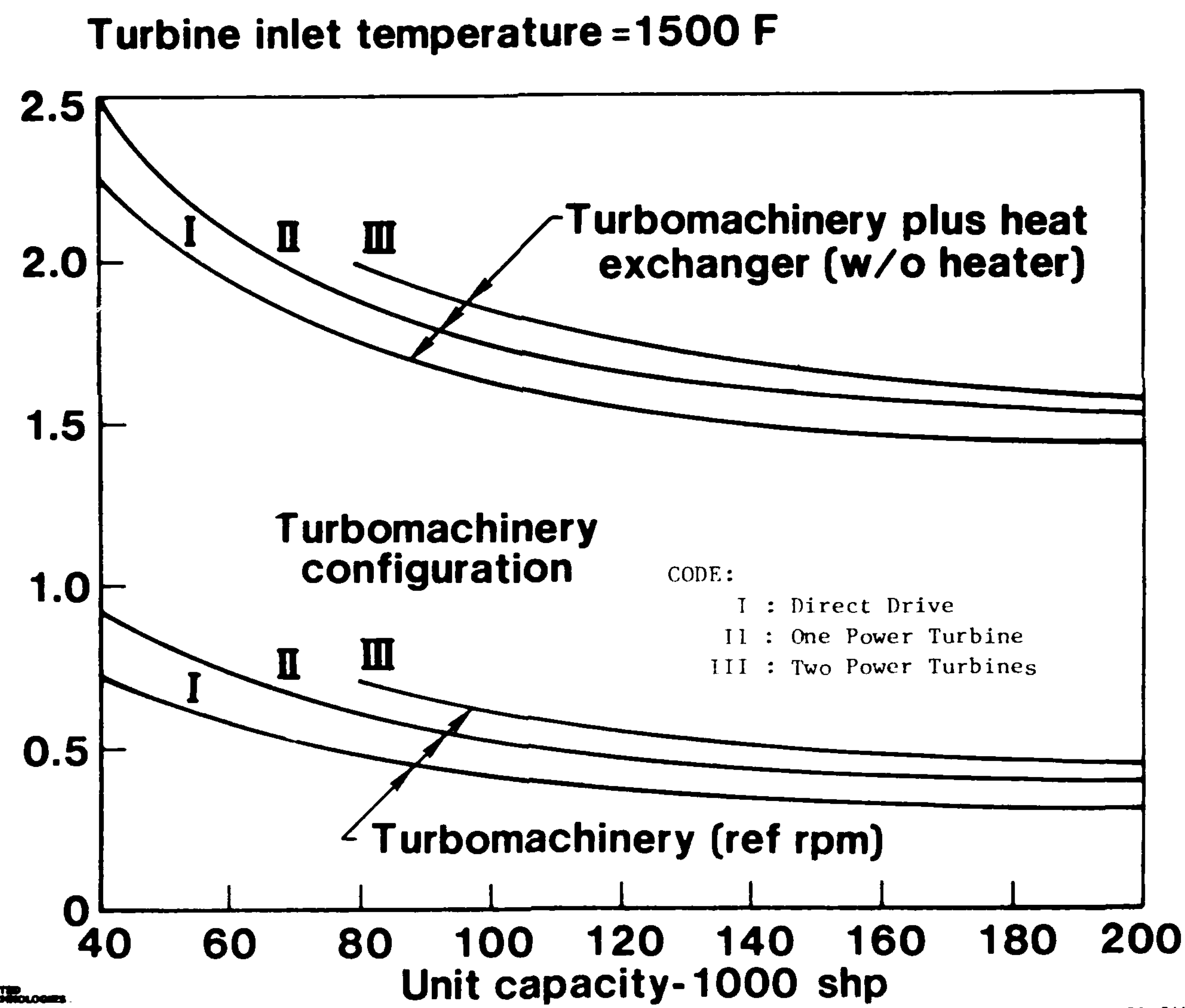
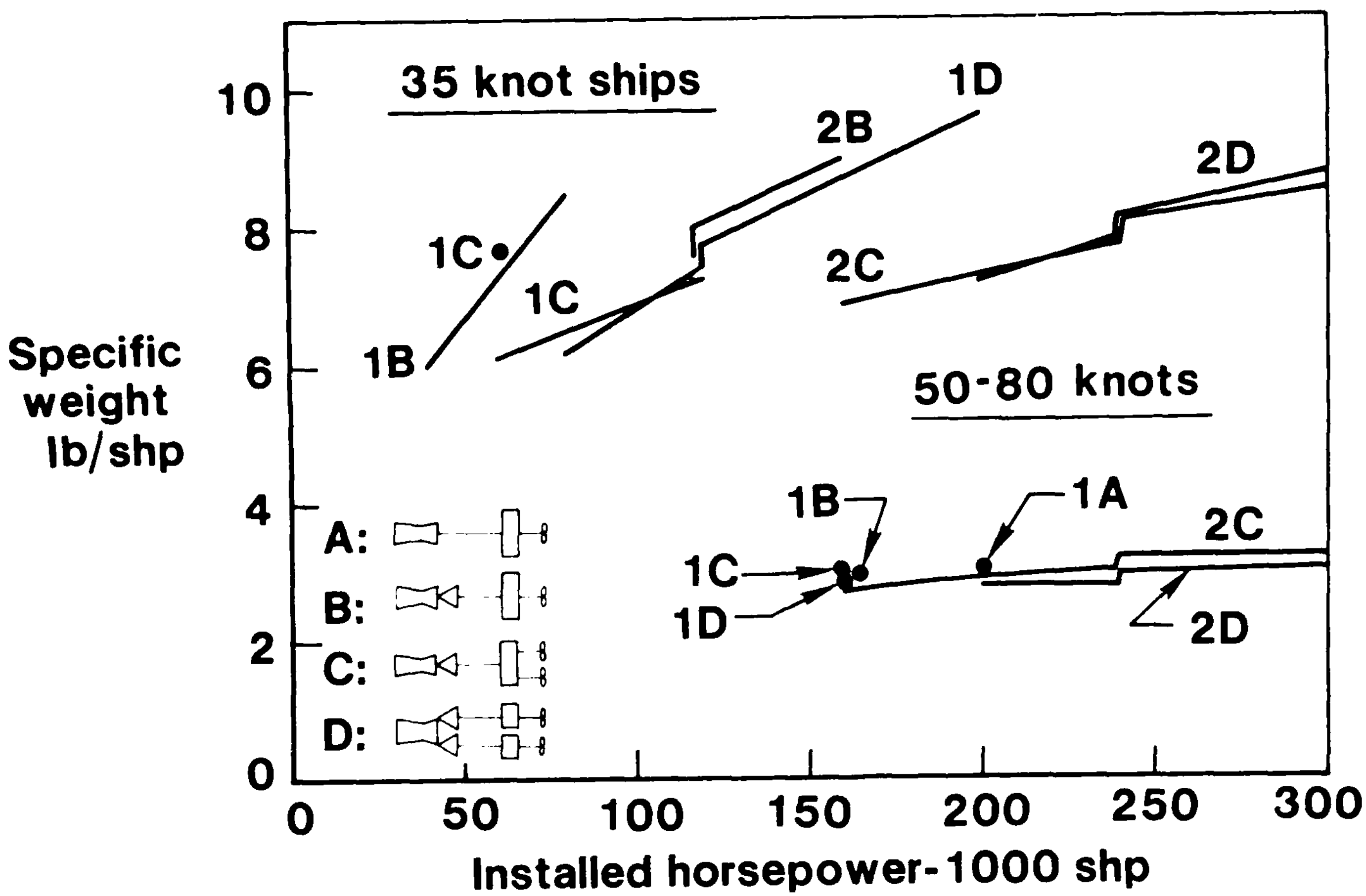


FIG. 1.11

Estimated CCGT Propulsion System Weight

Engine (w/o heater) + gear box + shafts



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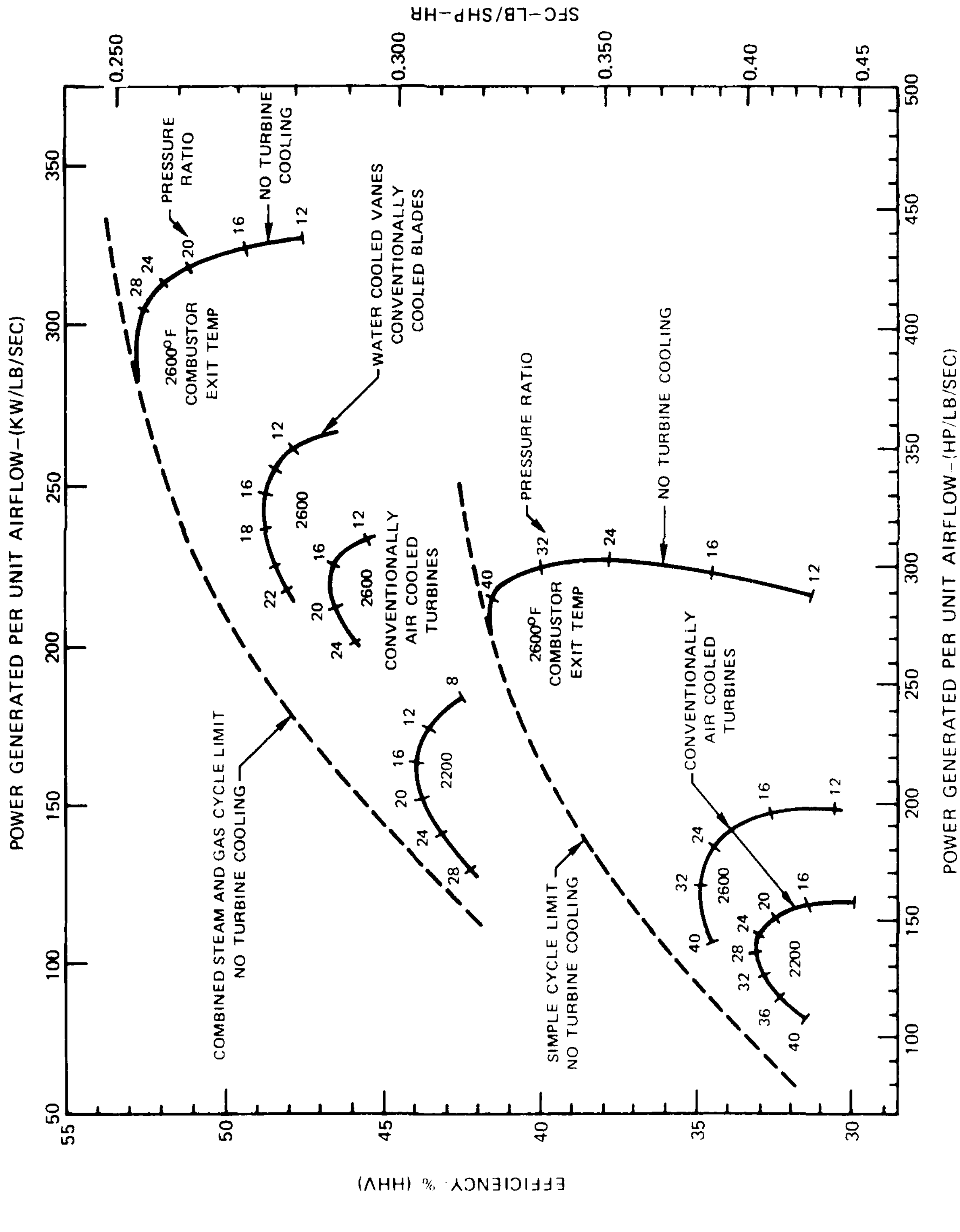
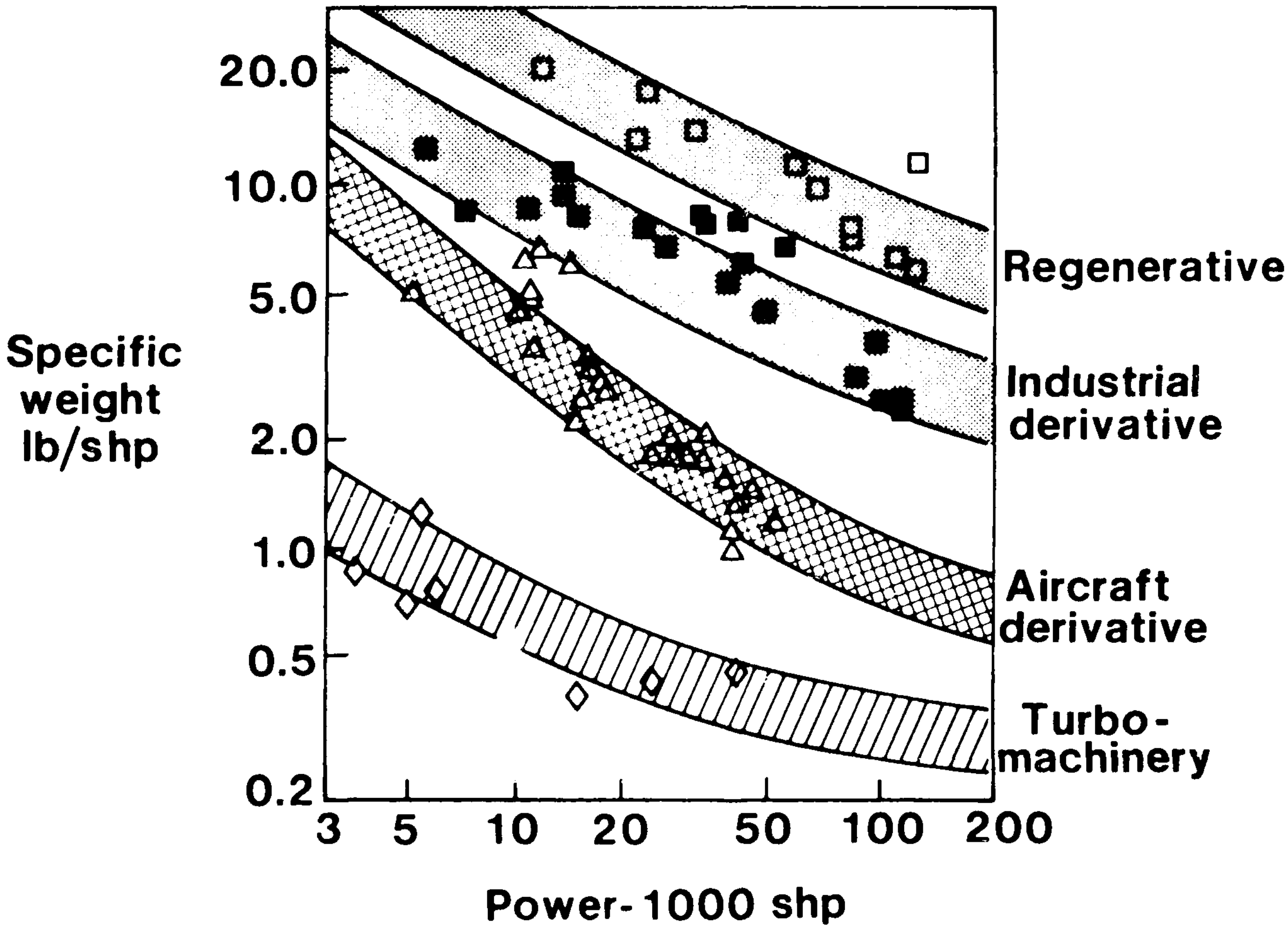
OPEN – CYCLE GAS TURBINE DESIGN POINT PERFORMANCE



Typical OCGT Specific Weights



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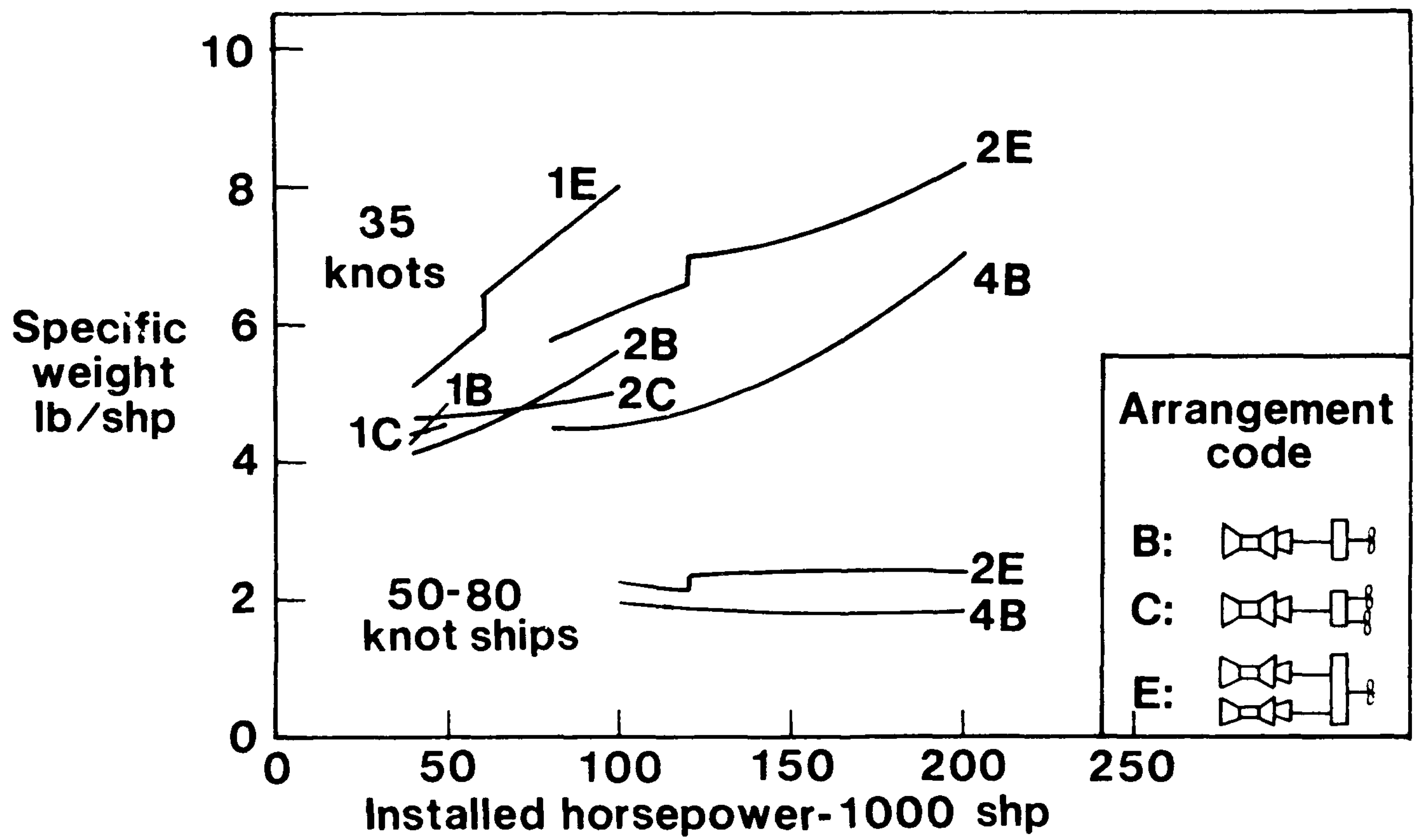
Estimated OCGT Propulsion Systems Weight

Engine + gearbox + shafts



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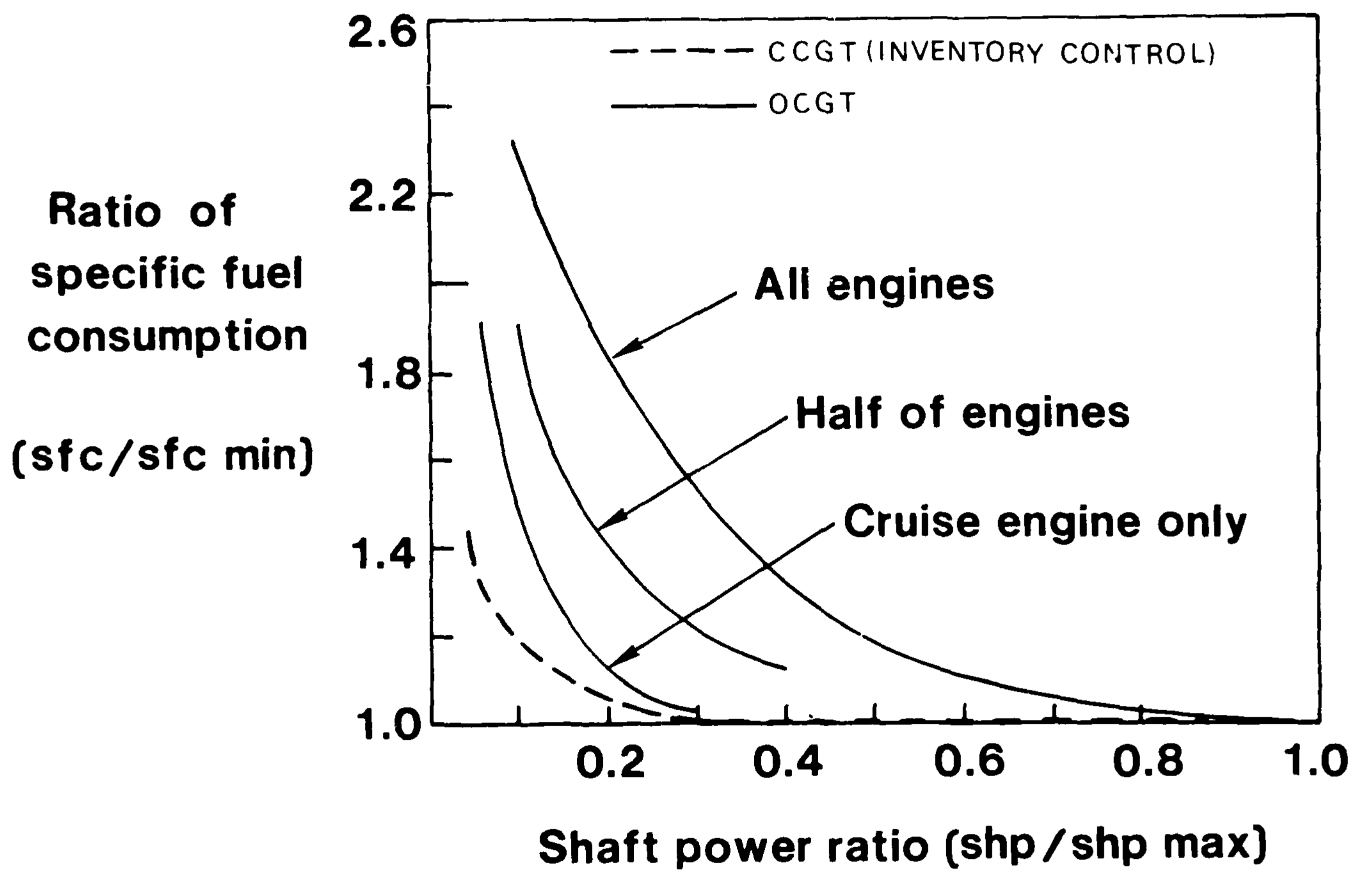
Typical Open- and Closed-Cycle Gas Turbine Part-Load Performance Characteristics



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Comparison of Engine Plus Fuel Specific Weight for High Speed Destroyers

Max. speed: 50 knots
Installed power: 160,000 shp

CCGT heater: 5 lb/shp fossil,
10-20 lb/shp nuclear

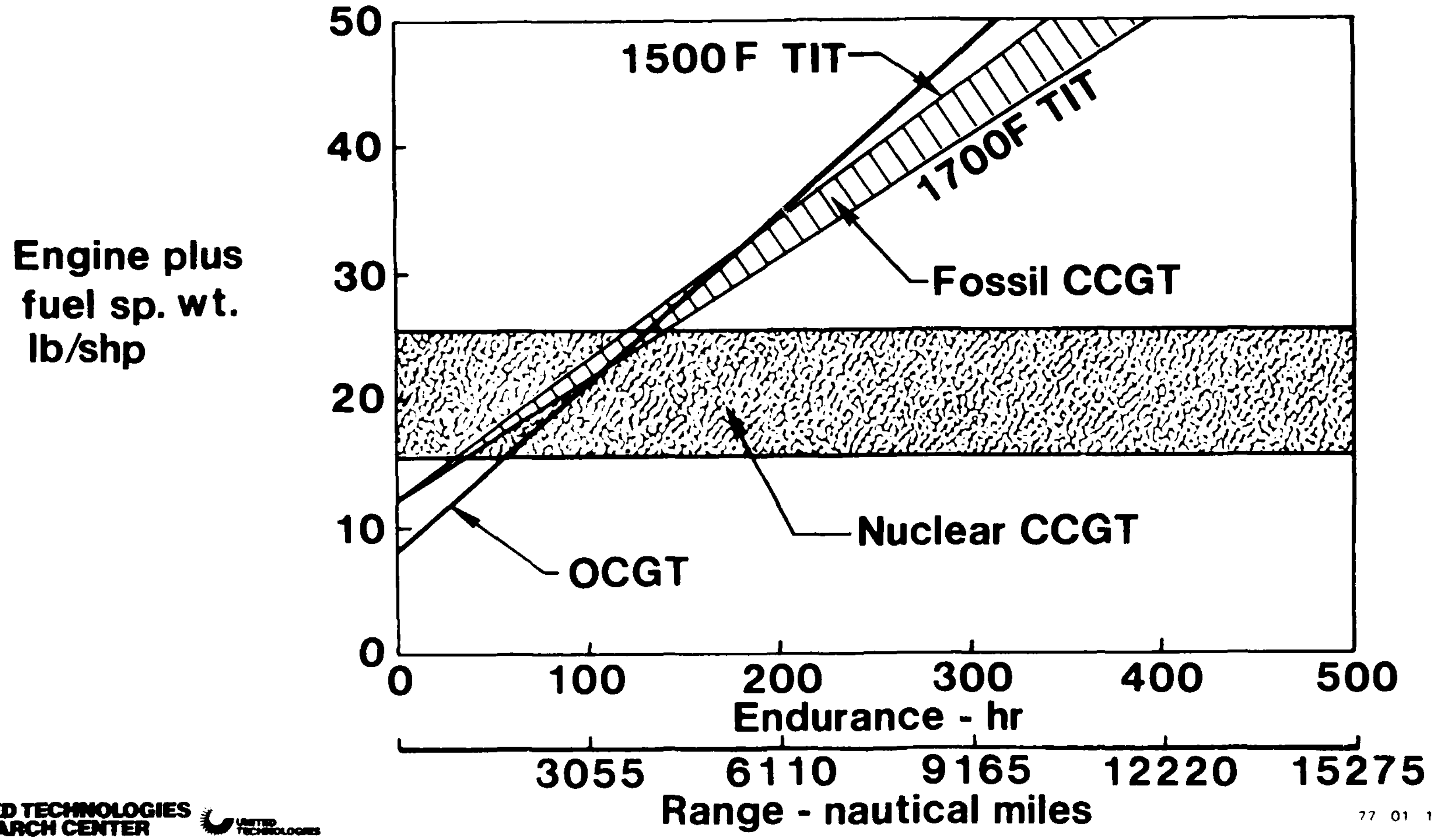

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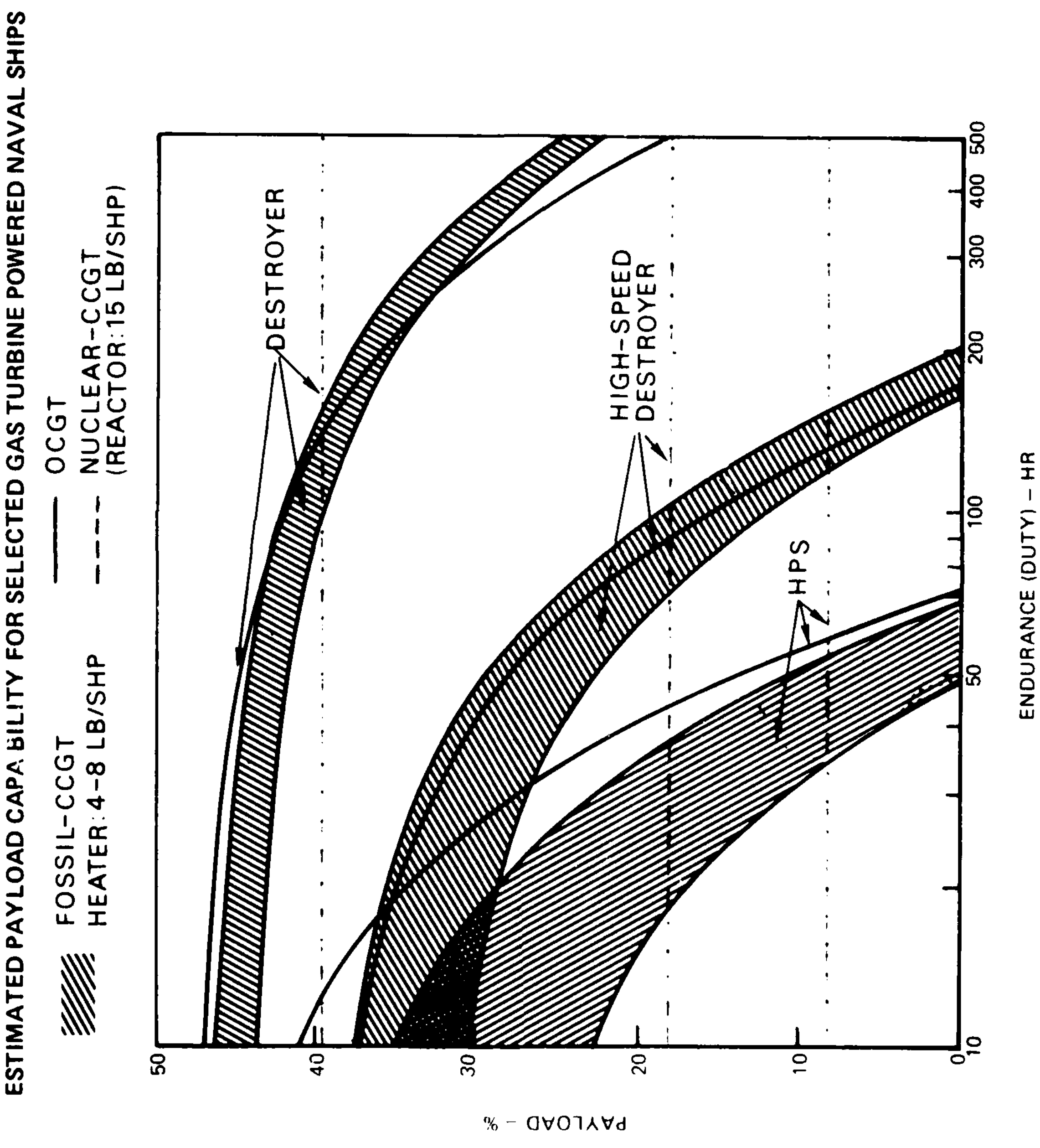
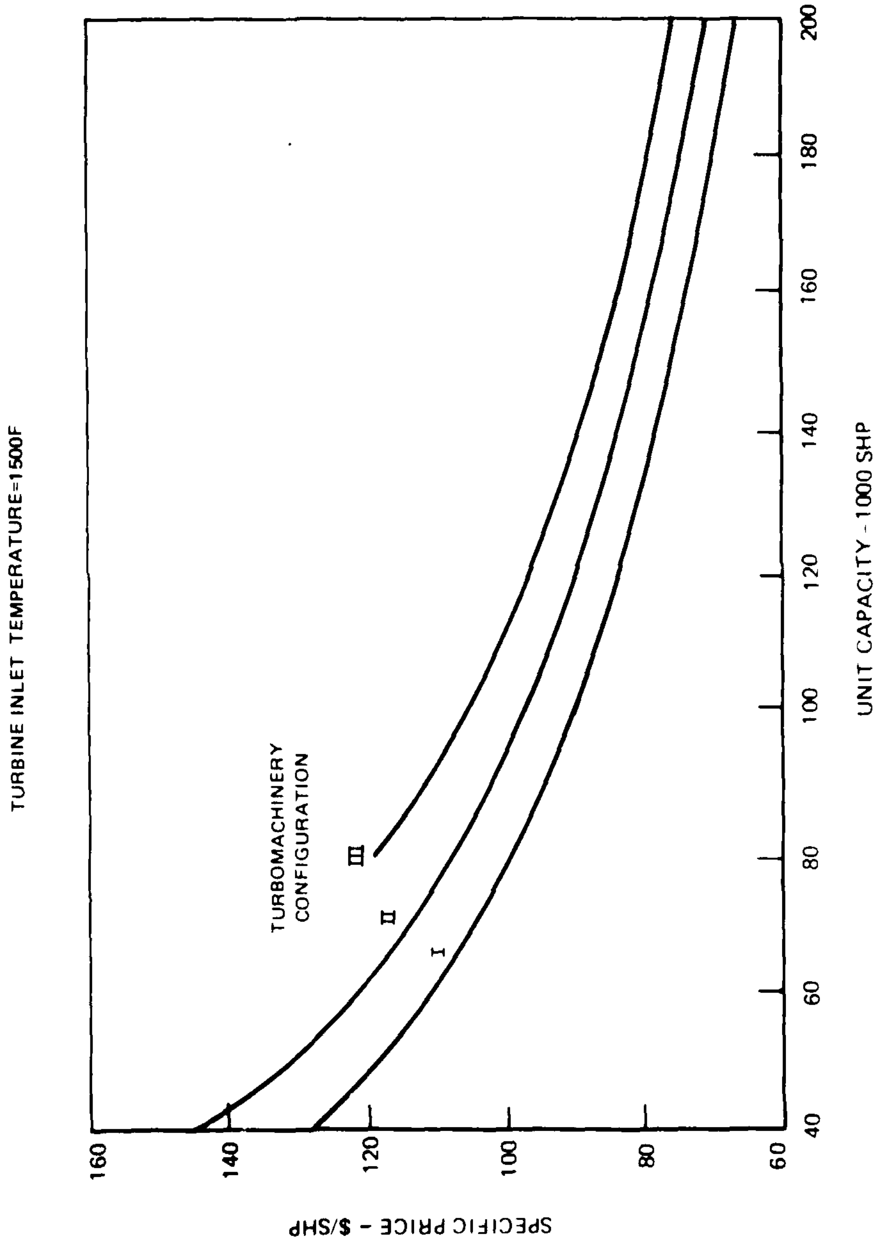
Fig. 1.17


ESTIMATED PAYLOAD CAPABILITY FOR SELECTED GAS TURBINE POWERED NAVAL SHIPS
FOSSIL-CCGT HEATER: 4-8 LB/SHP
OCGT
NUCLEAR-CCGT (REACTOR: 15 LB/SHP)
DESTROYER
HIGH-SPEED DESTROYER
HPS
PAYLOAD – %
ENDURANCE (DUTY) – HR
50
40
30
20
10
0
10
50
100
200
300
400
500

ESTIMATED CCGT POWER CONVERSION SYSTEMS SELLING PRICE



Estimated Response for CCGT Drop Load Condition

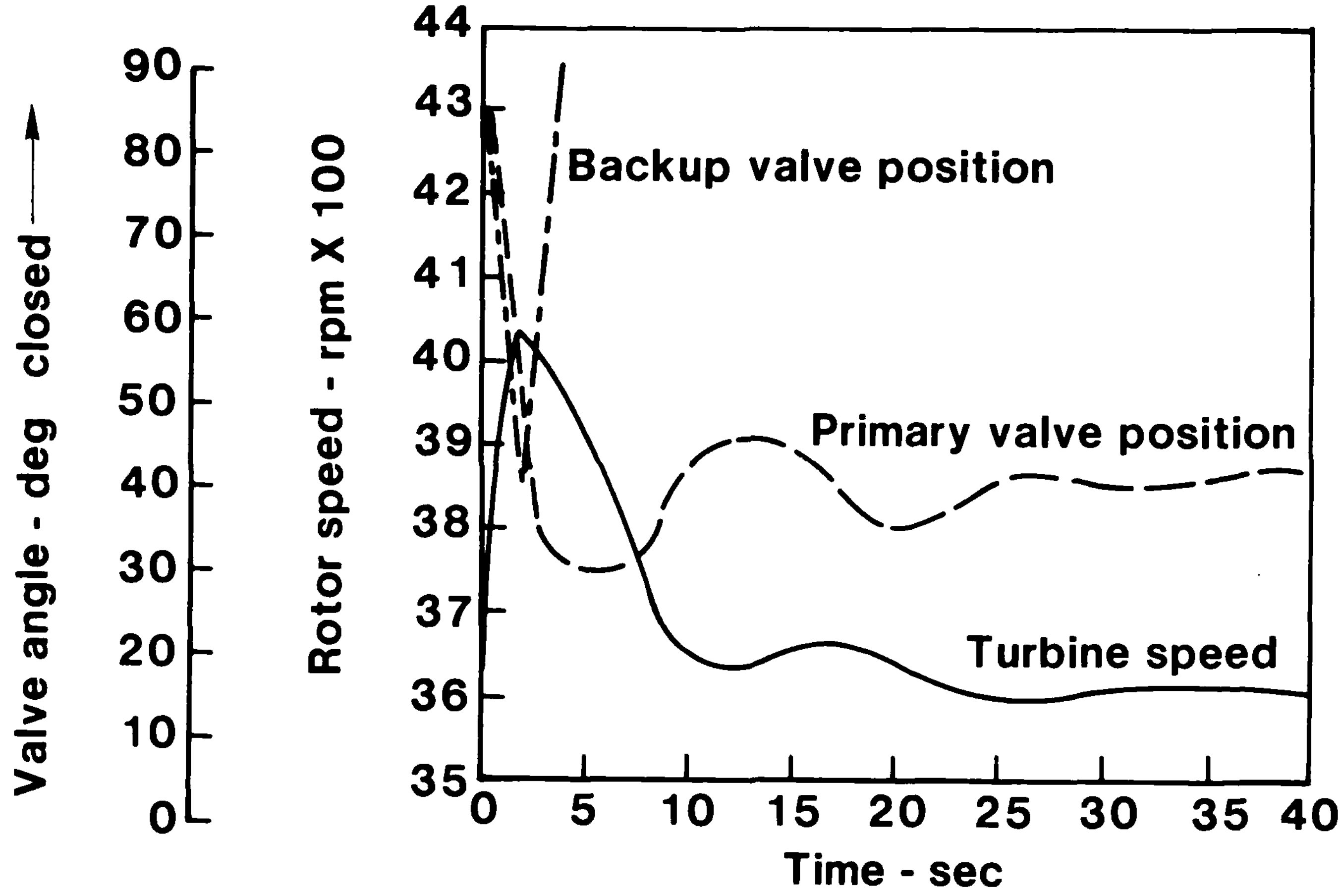


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Fig. 1.20

Schematic Diagrams of Alternative Fossil-Fired Heater Systems

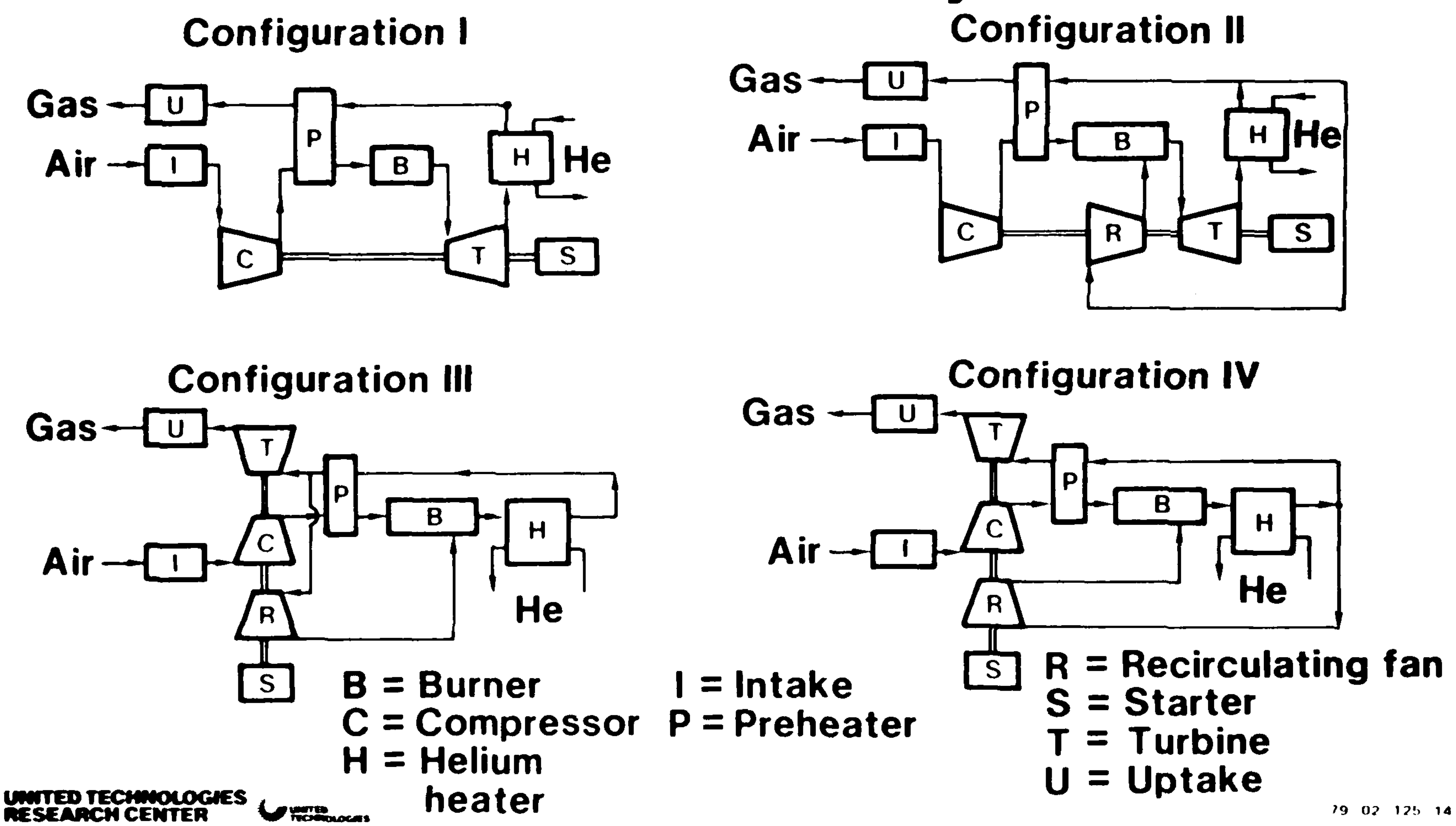

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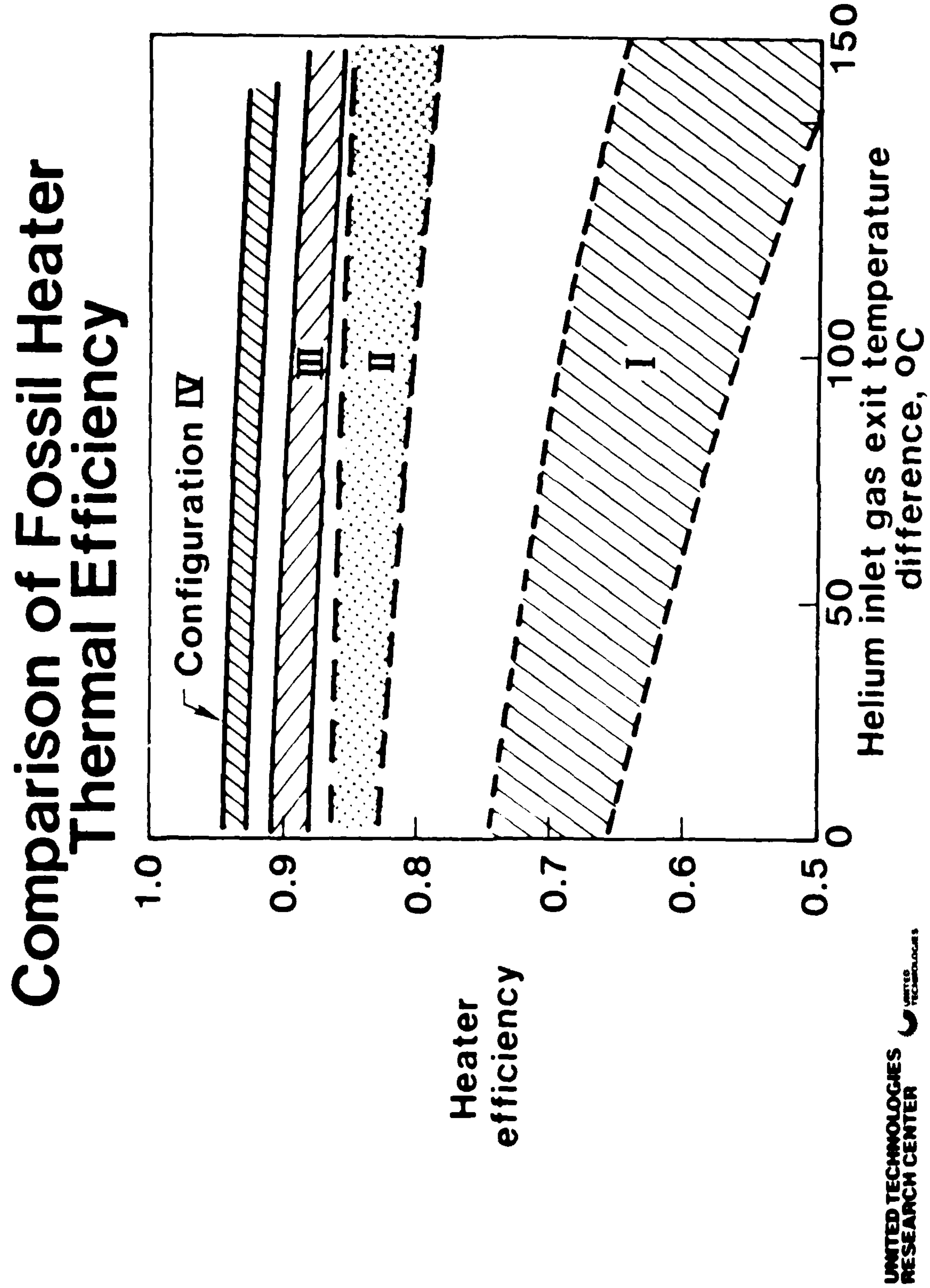
Fig. 2.2



Comparison of Fossil Heater Thermal Efficiency
Heater efficiency
1.0
0.9
0.8
0.7
0.6
0.5
0
50
100
150
Helium inlet gas exit temperature difference, °C
Configuration IV
III
II
I
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LWSP FOSSIL HEATER SYSTEM WEIGHT AND COST CHARACTERISTICS

- PROPULSION POWER = 59680 kW (80,000 SHP)
- COMPRESSION RATIO = 4.0
- MAXIMUM METAL TEMP = 950°C
- TOTAL PRESSURE DROP = 117.6 TO 212.5 IN. H_2O

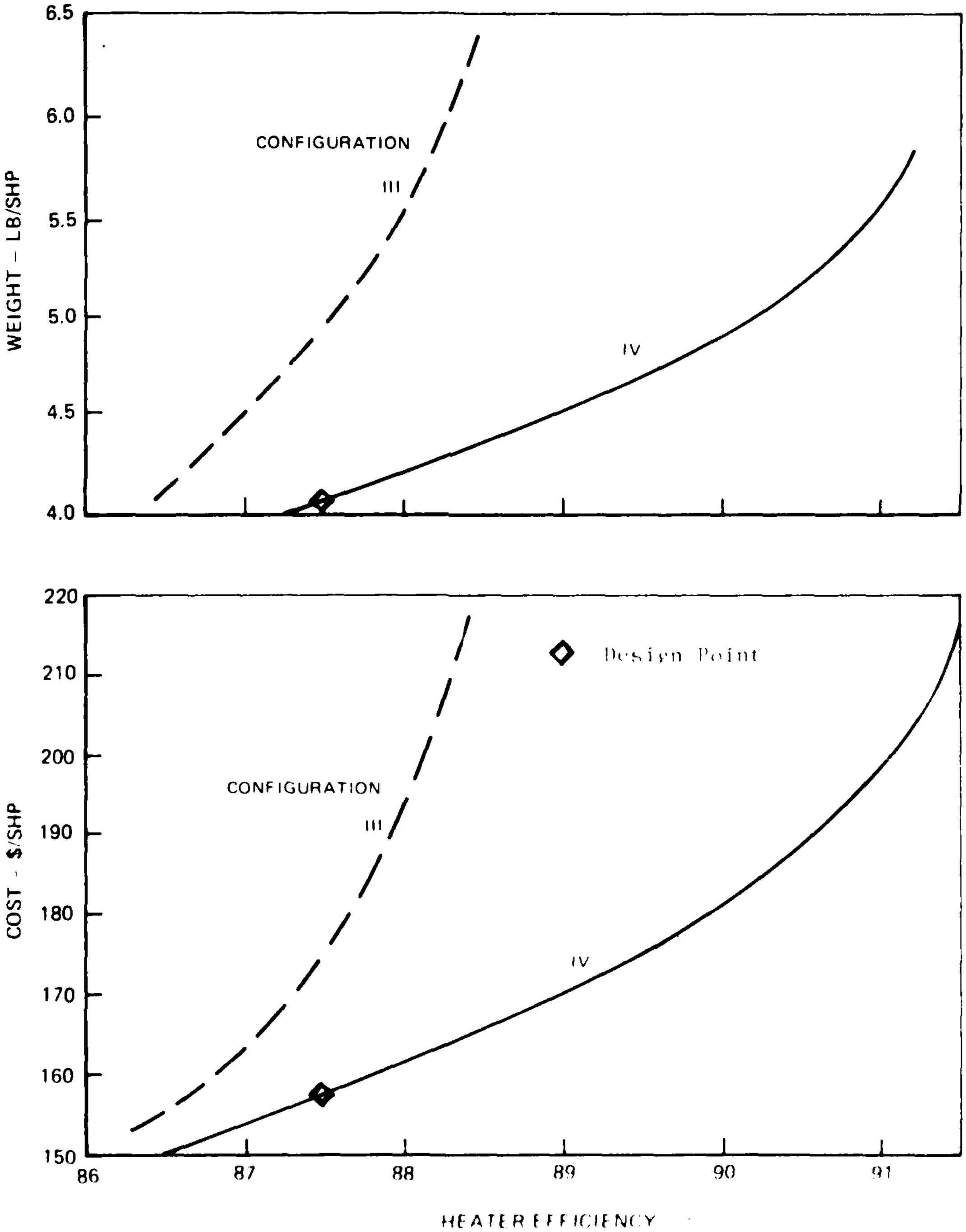
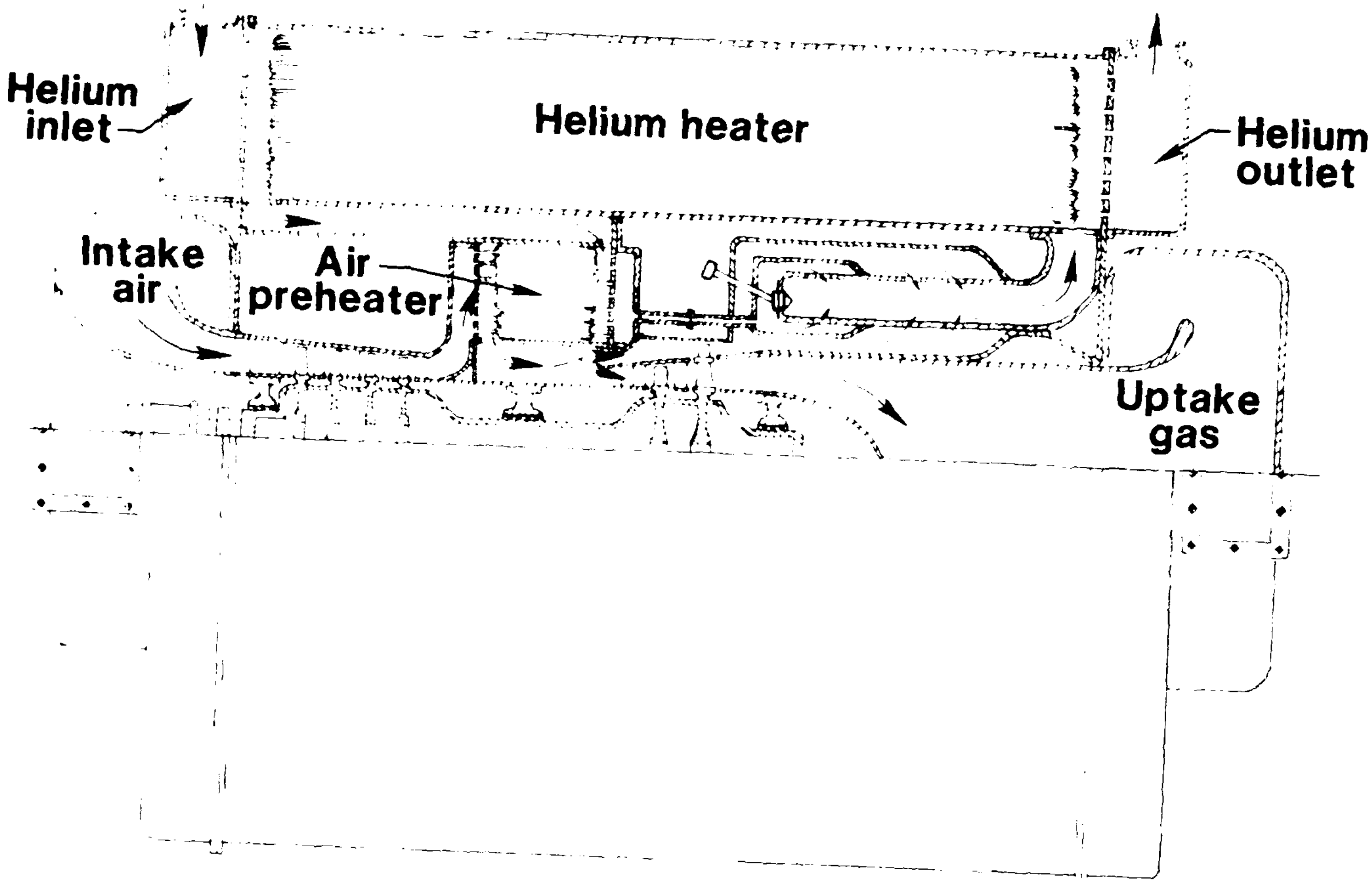


Fig. 2.4

LWSP Fossil Heater Configuration IV Design Concept



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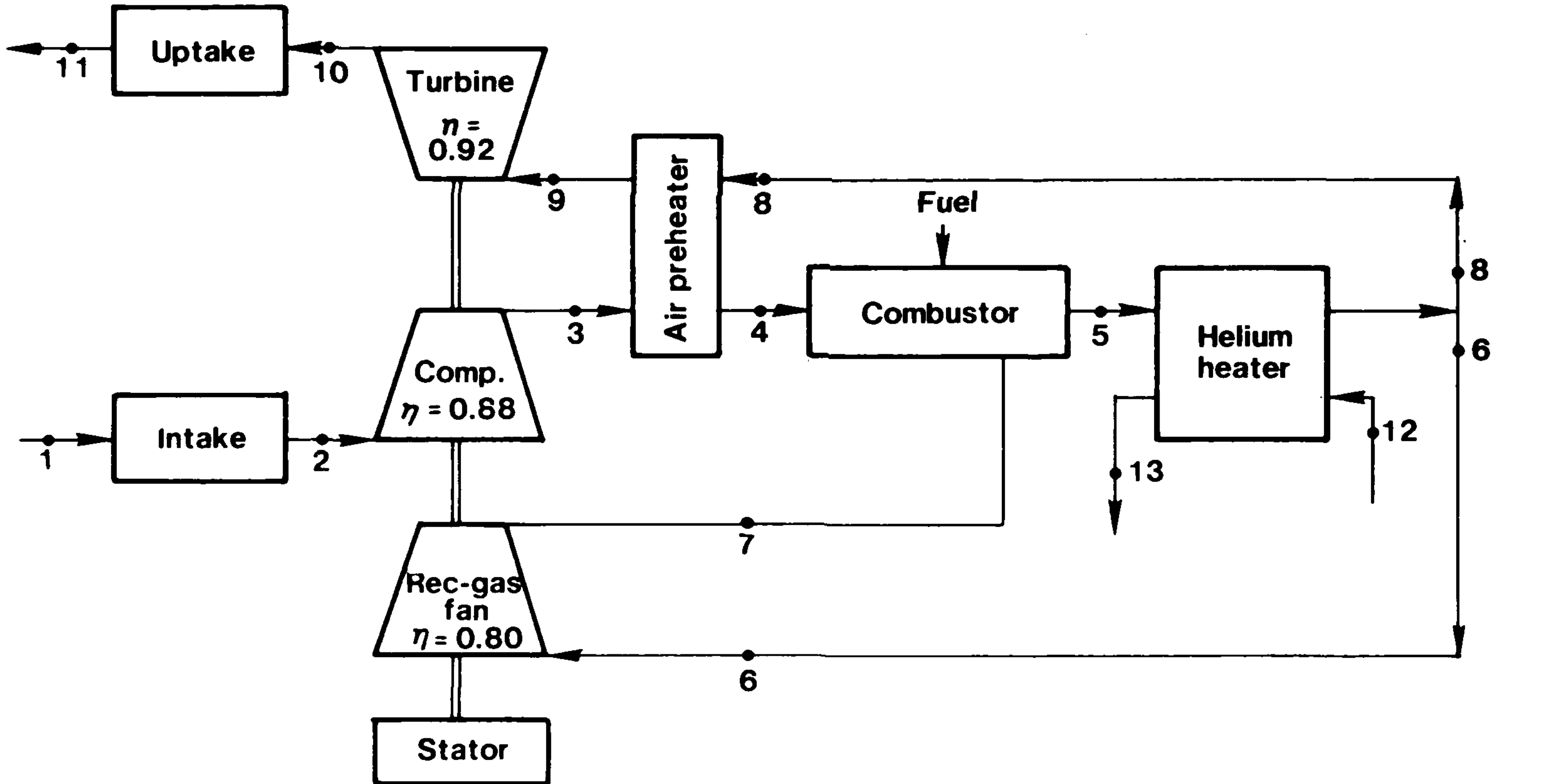
Cycle Definitions of Preferred Fossil-Heater System

- CCHT propulsion power=59.7 mw
- Overall heater thermal efficiency=87.5

Station		1	2	3	4	5	6	7	8	9	10	11	12	13
Fluid		Air				Combustion gas							Helium	
Flow rate	kg/sec	68.88				194.64	121.79		72.85				75.22	
Temperature	C	26.7	26.7	191.1	249.0	1093	481.0	500.0	481	430	252	247	453	816
Pressure	atm	1.00	0.97	3.88	3.78	3.76	3.48	3.76	3.48	3.39	1.02	1.01	45.36	44.23



80,000-SHP CCGT Propulsion System Integration

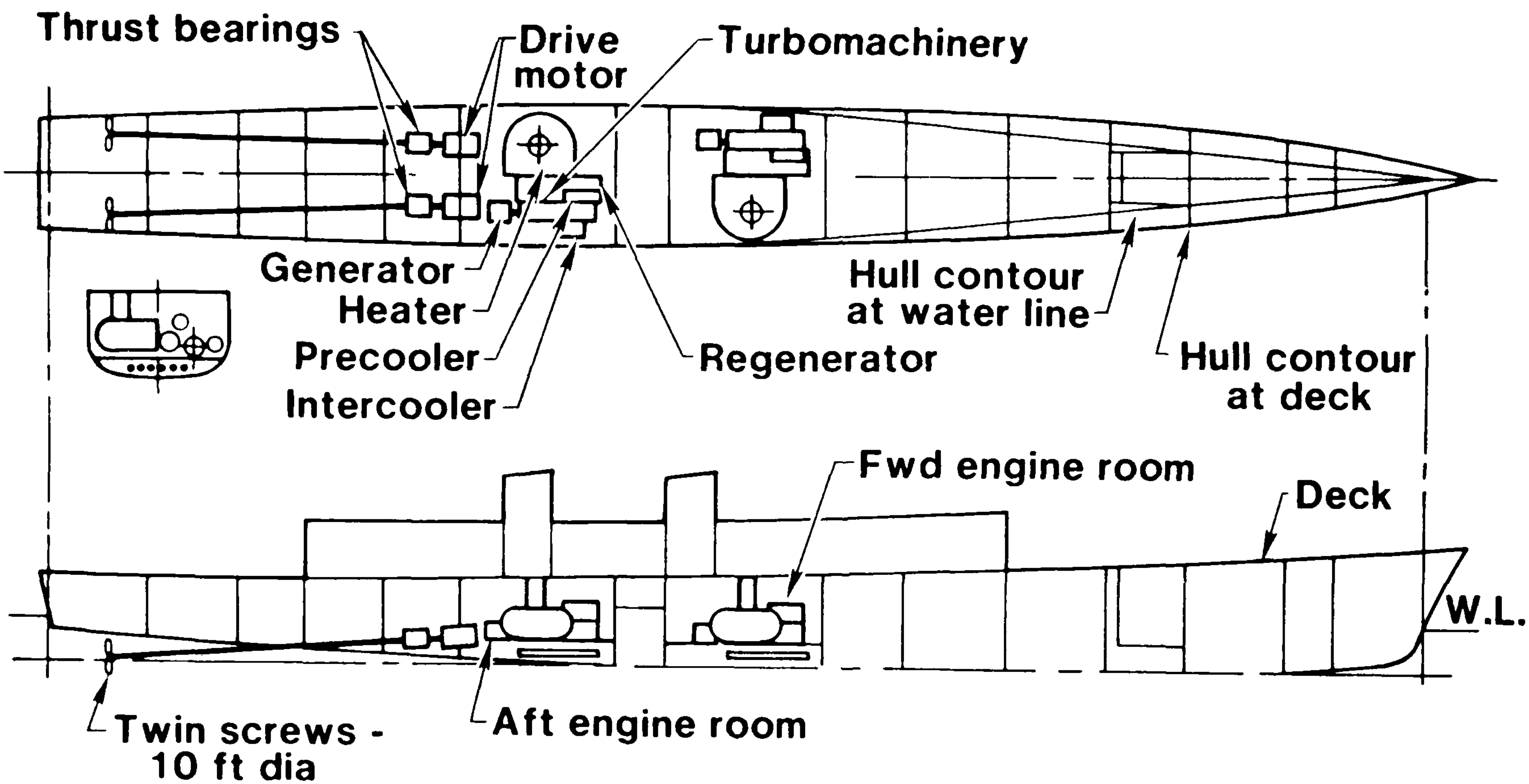


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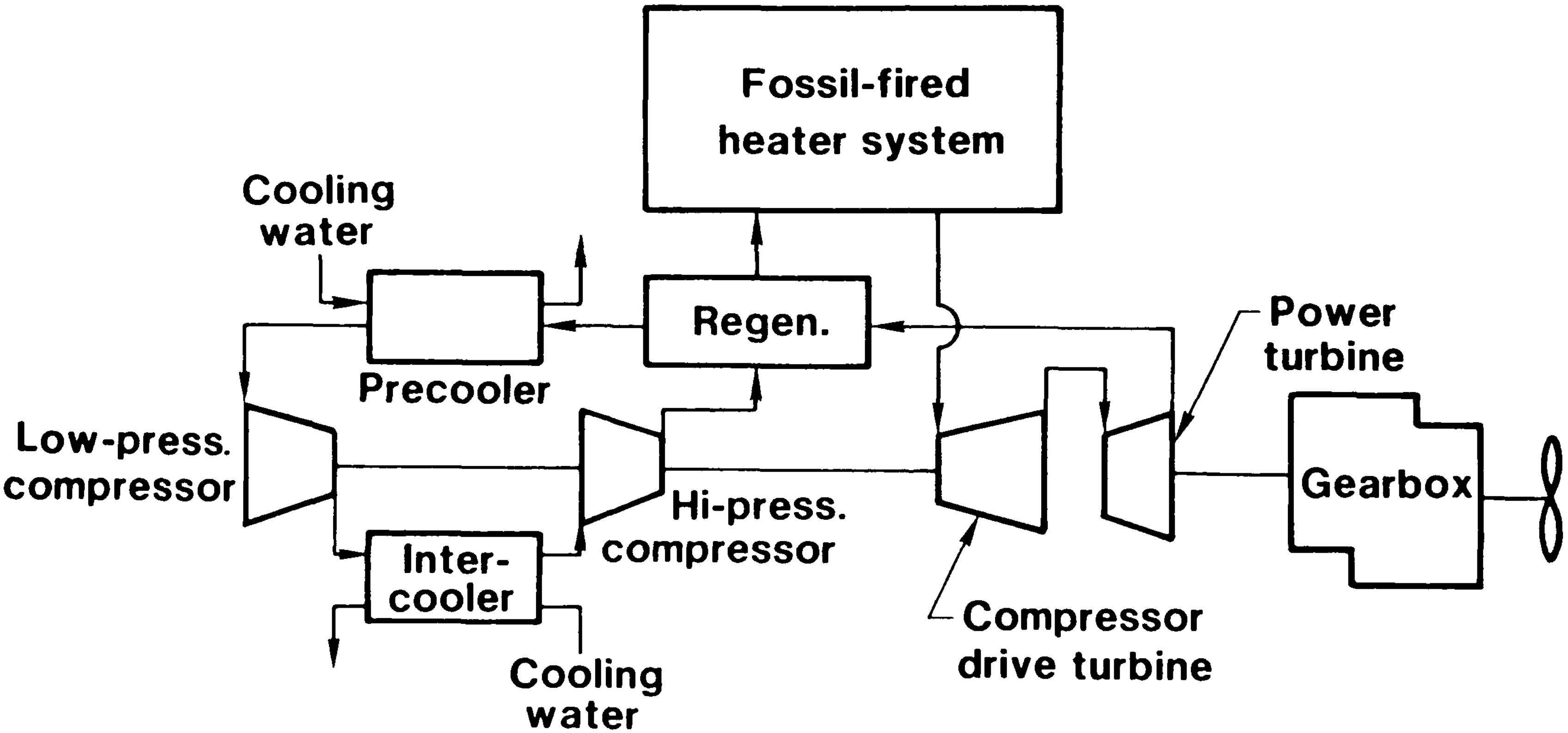
Fig. 2.6

Fig. 2.

Schematic Diagram of Fossil-Fired Closed-Cycle Helium Turbine Propulsion System



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CONCEPTUAL DESIGN OF HELIUM CCGT TURBOMACHINERY

• RATING–59.7 MW (80,000 shp)

Pratt & Whitney Aircraft Group

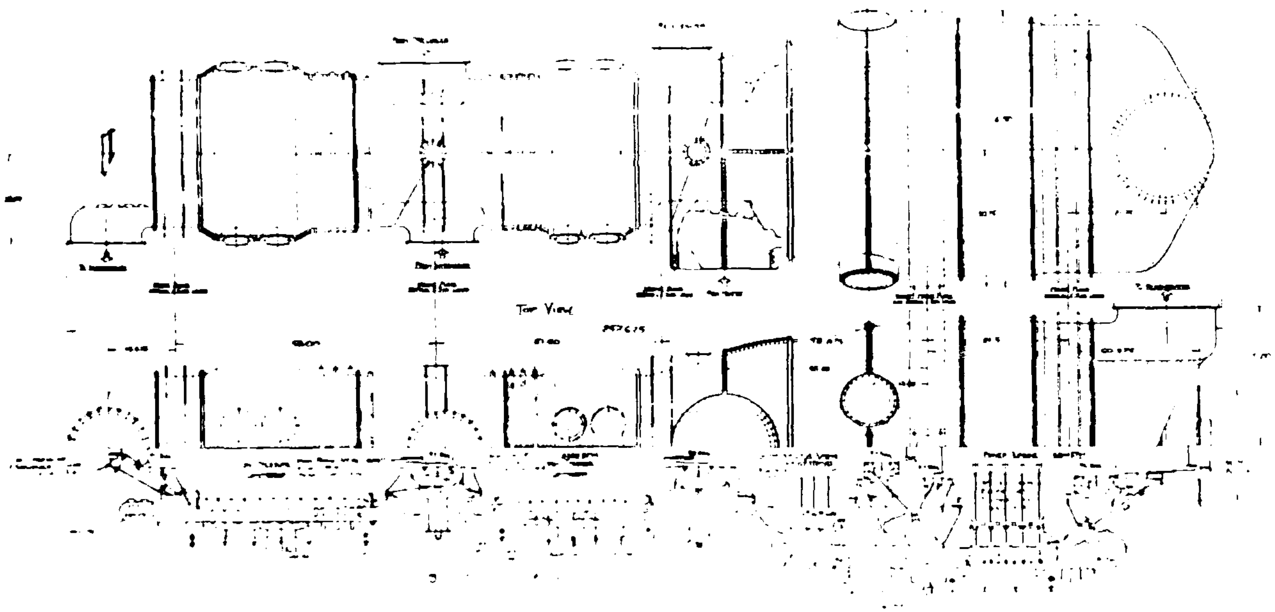
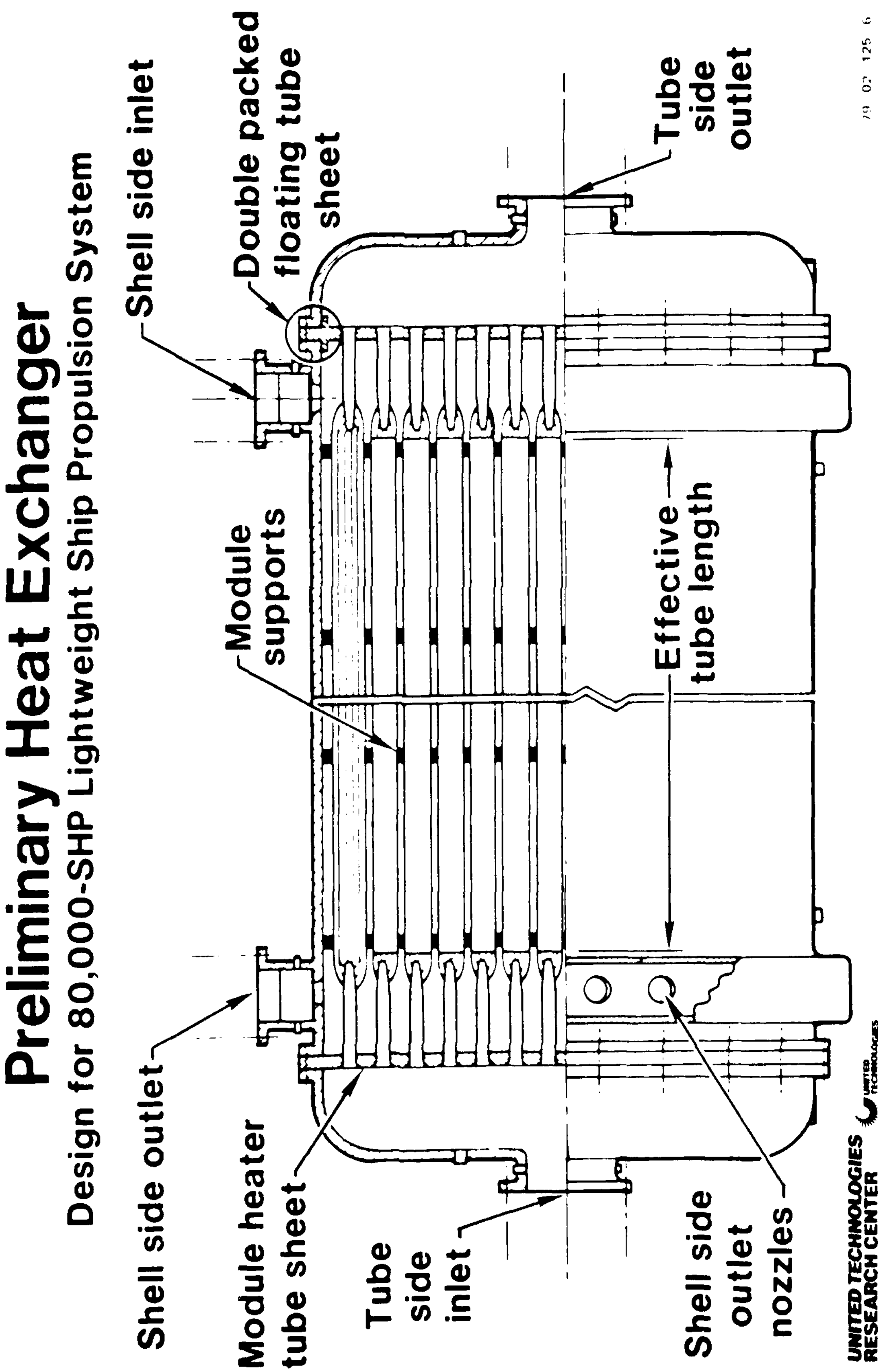


FIG. 2.8


Preliminary Heat Exchanger
Design for 80,000-SHP Lightweight Ship Propulsion System
Shell side inlet
Double packed floating tube sheet
Tube side outlet
Module supports
Effective tube length
Shell side outlet
Module heater tube sheet
Tube side inlet
Shell side outlet nozzles
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High-Speed Destroyer Propulsion System Layout

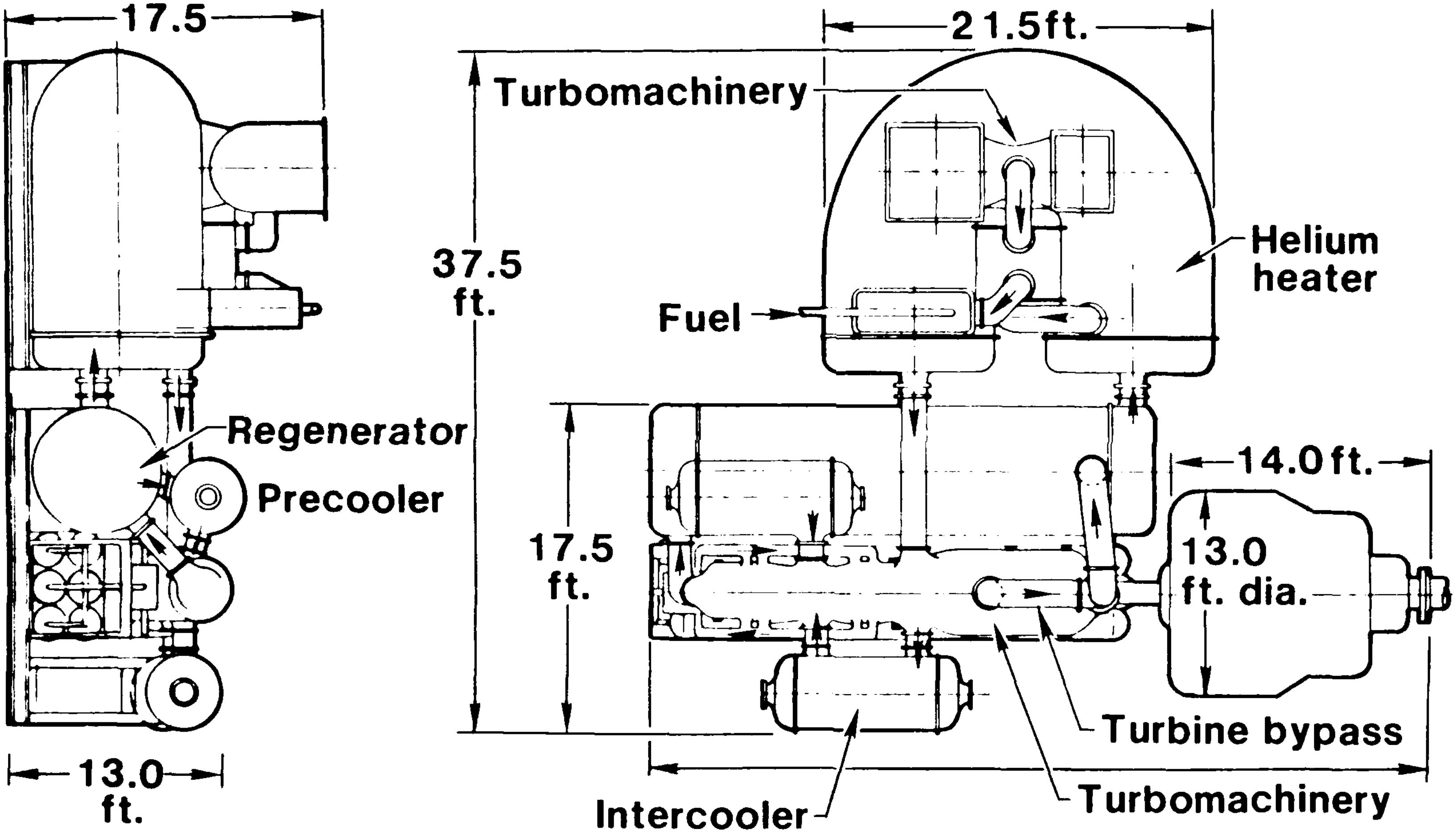

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Fig. 2.10

High Speed Destroyer Propulsion System

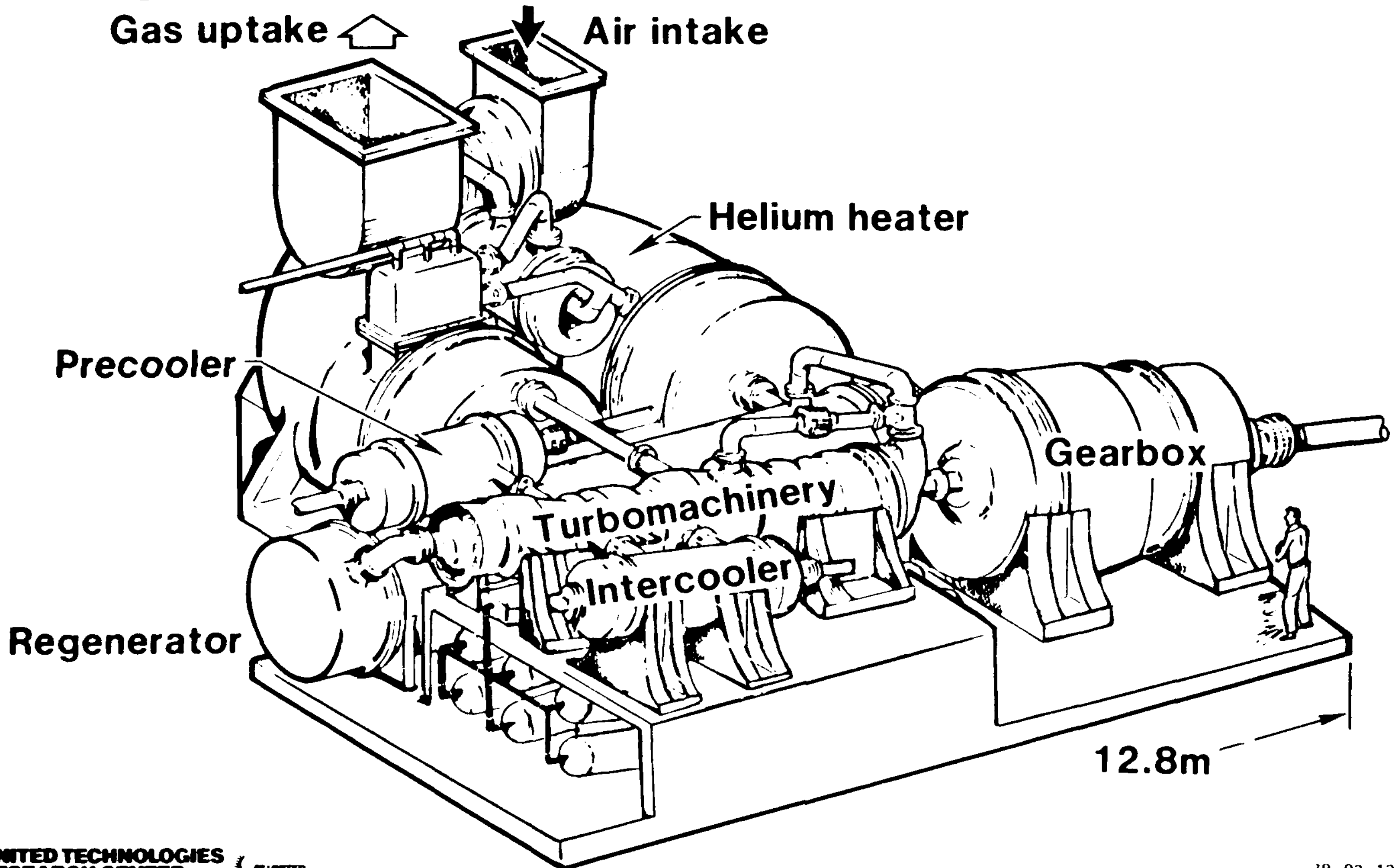

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Fig. 2.11

FIG. 2.12

CCGT–LWSP PRELIMINARY CONTROL REQUIREMENTS

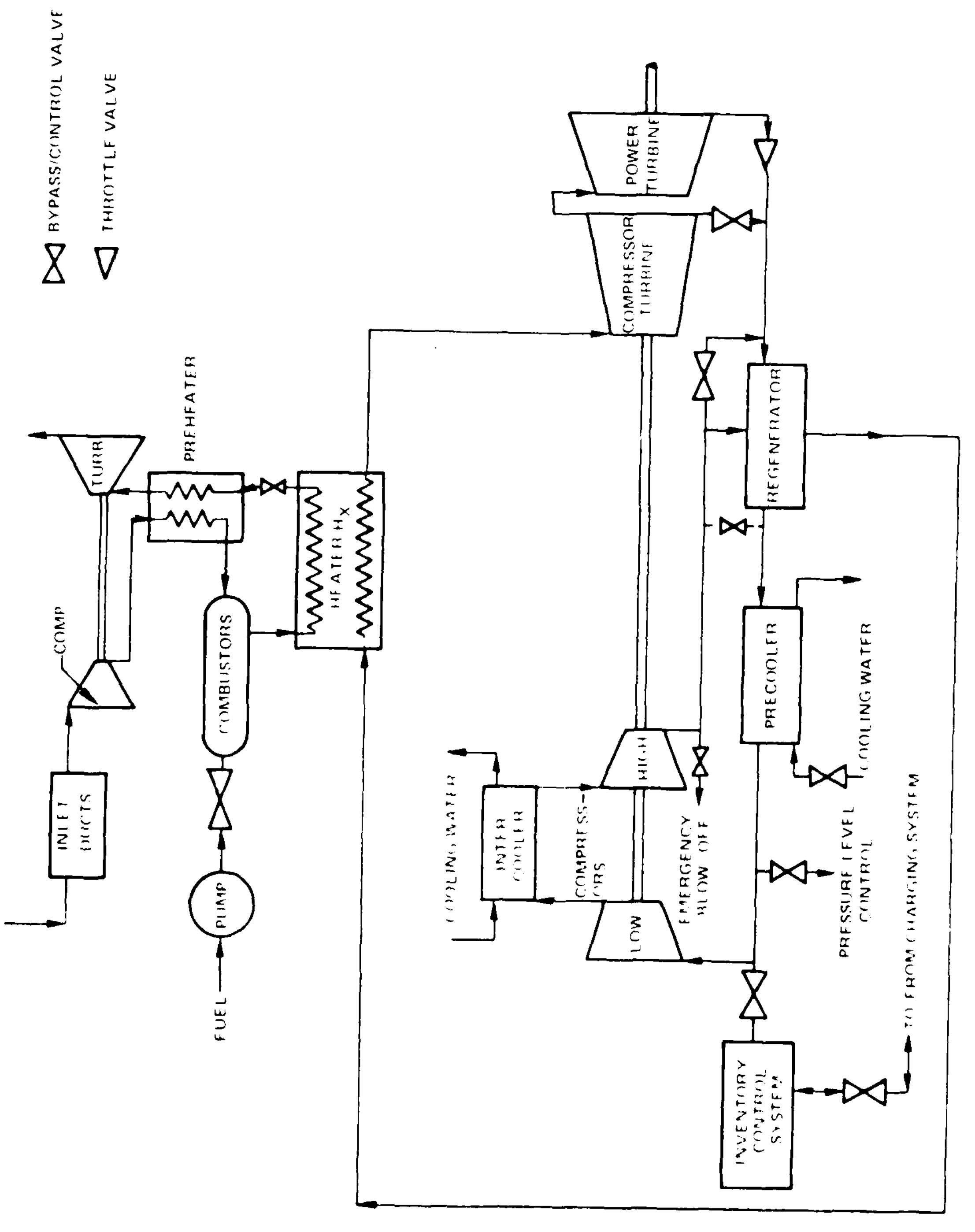
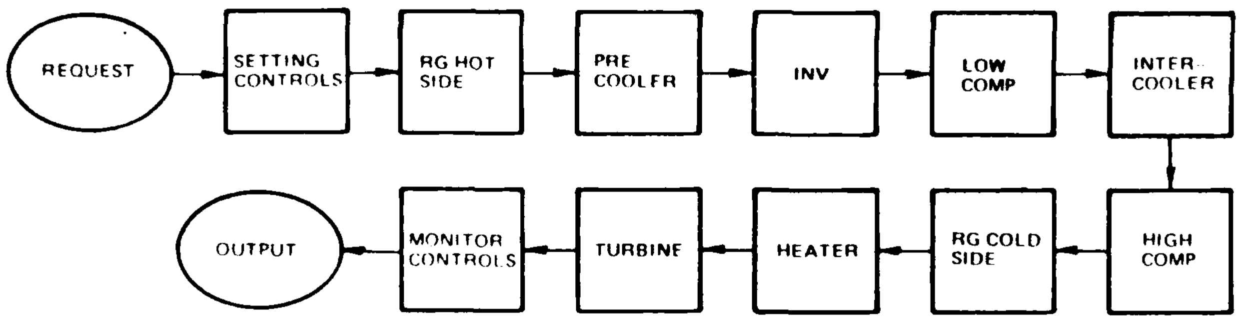


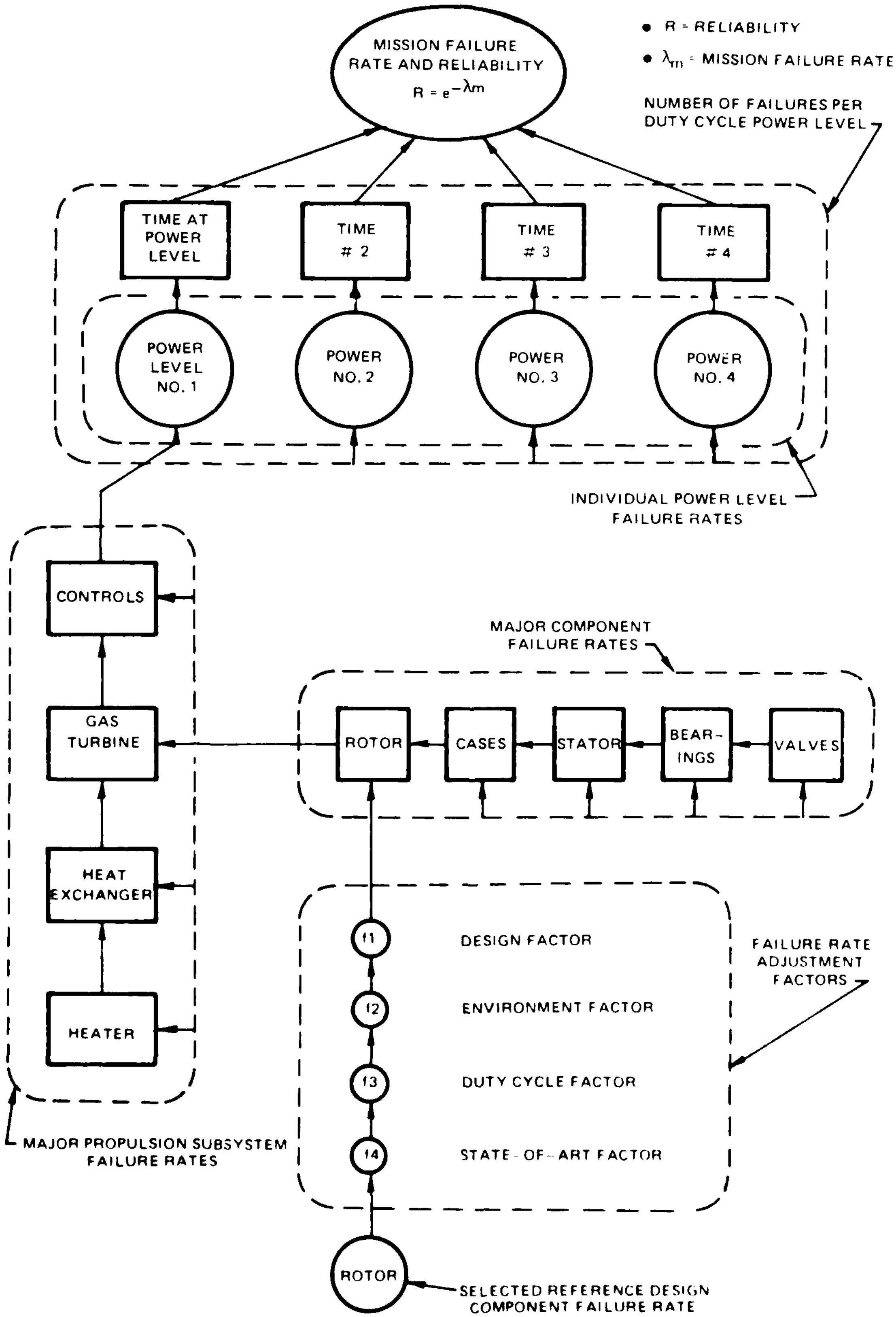
FIG. 2.13

OVERALL LWSP–CCGT POWER SYSTEM RELIABILITY BLOCK DIAGRAM

- MAJOR SUBSYSTEMS
- INV - INVENTORY SUBSYSTEM
- RG - REGENERATOR SUBSYSTEM
- COMP COMPRESSOR SUBSYSTEM



LSWP RELIABILITY ESTIMATION METHODOLOGY



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Comparison of Projected Mission Reliabilities for CCGT and Steam Propulsion Systems

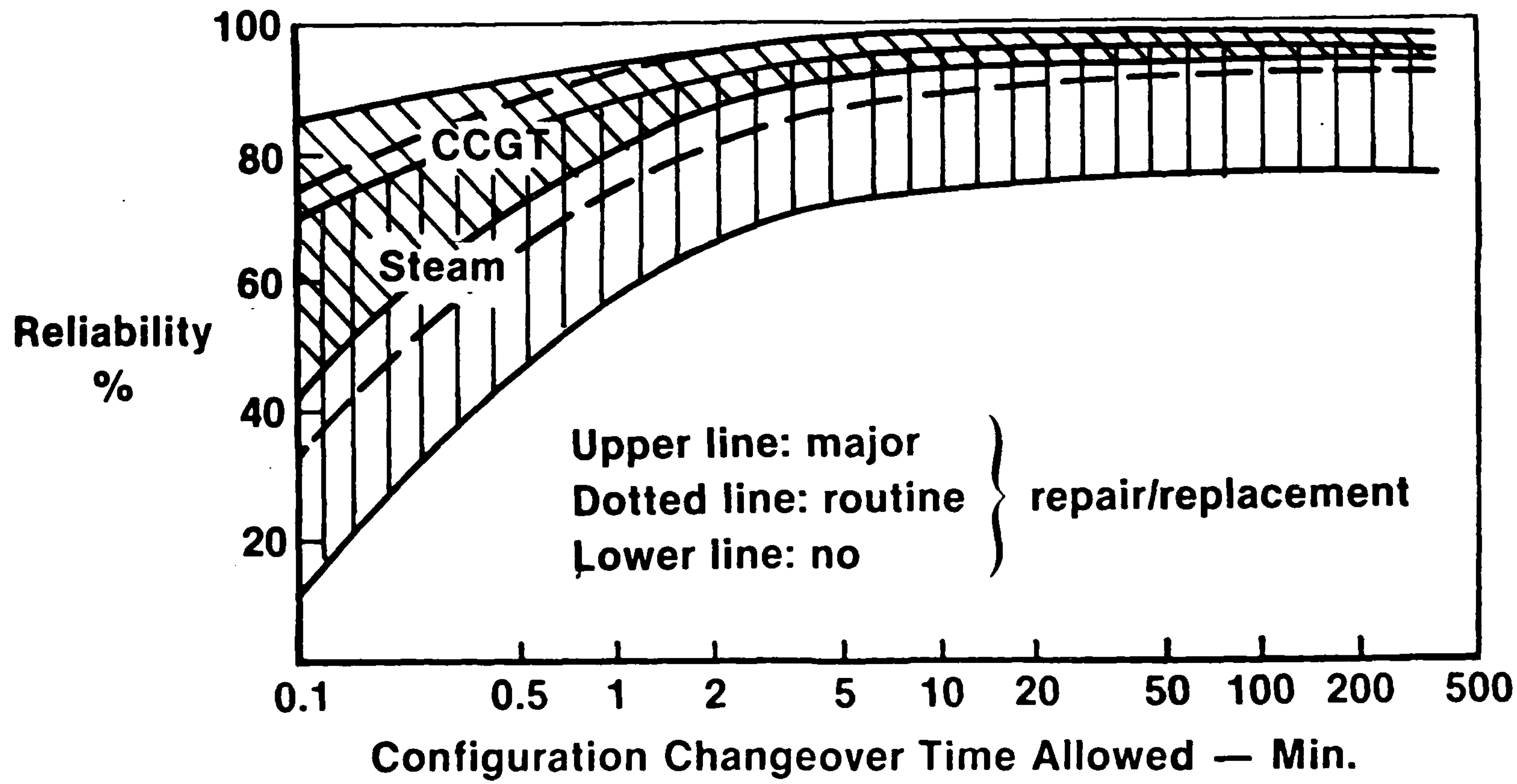

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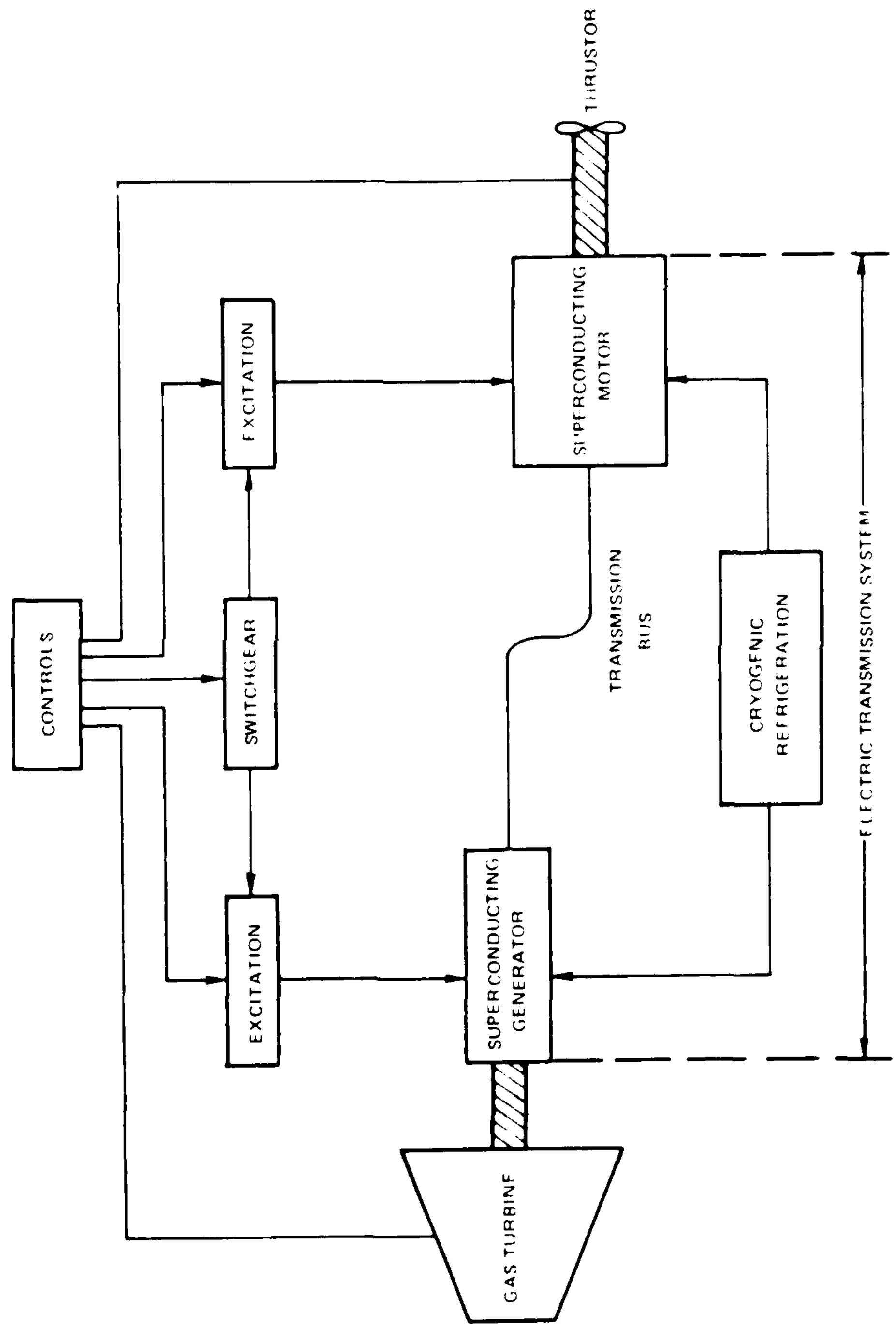
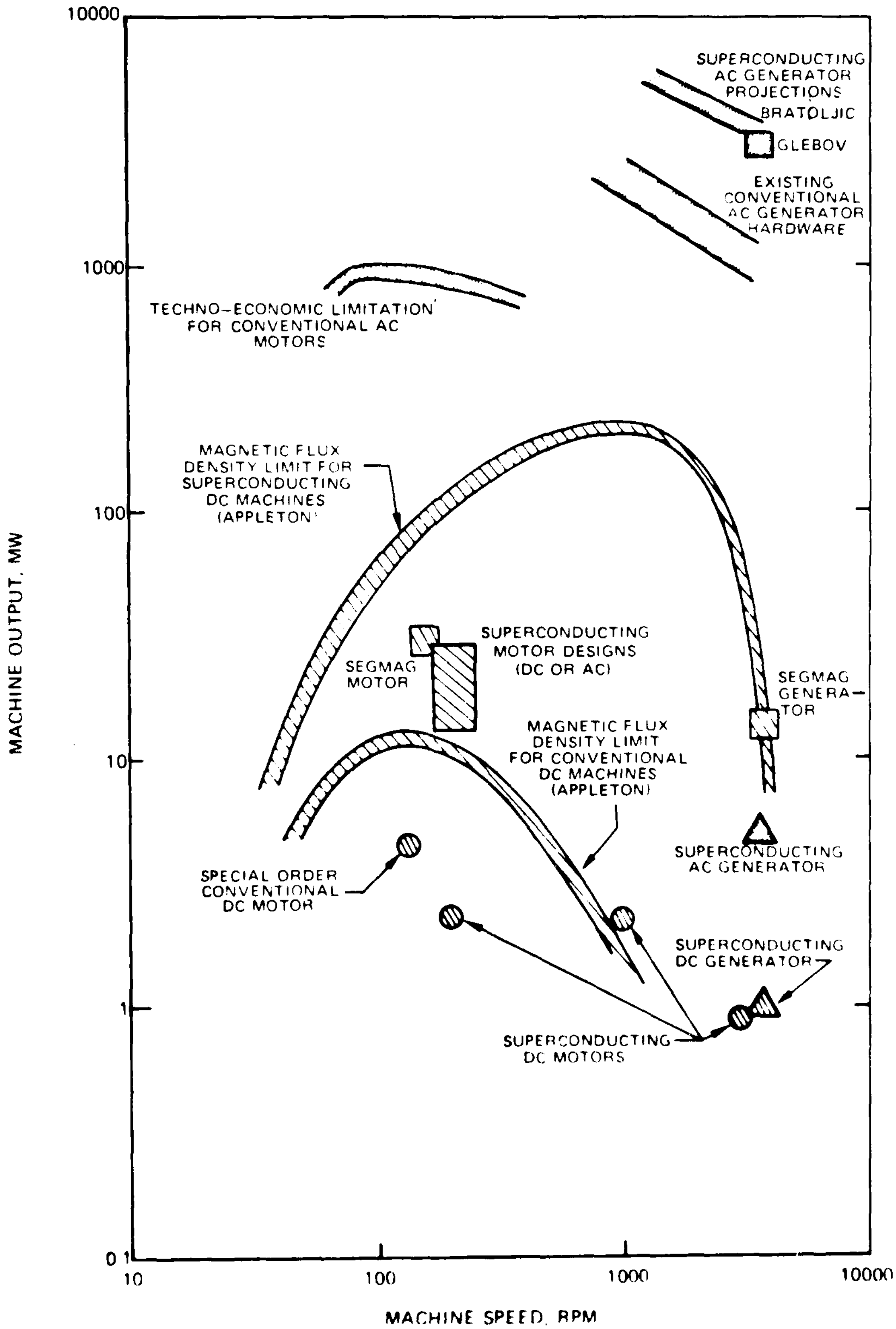
Fig. 2.15

SCHEMATIC OF SUPERCONDUCTING ELECTRIC TRANSMISSION SYSTEM

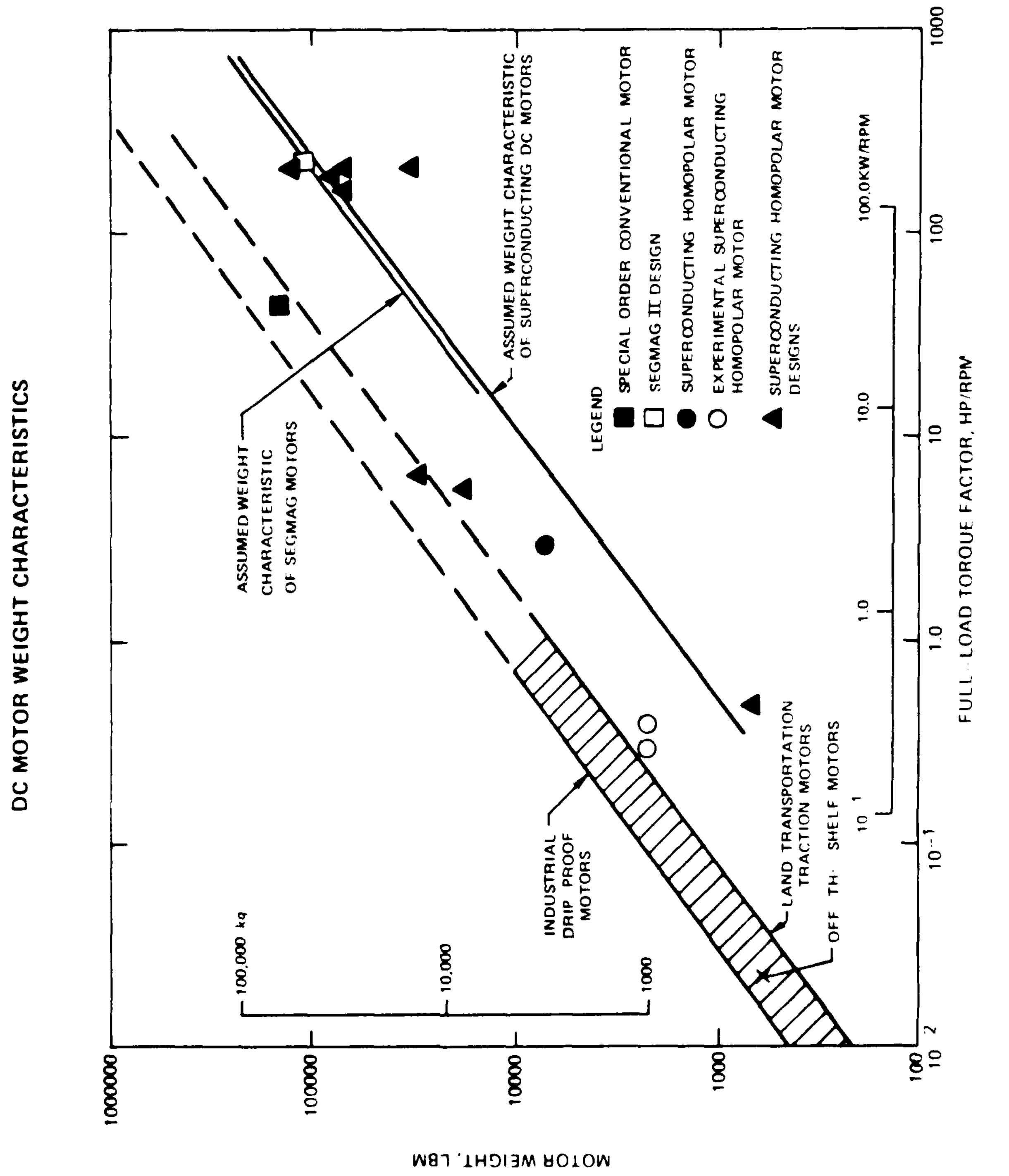


CAPACITY LIMITS OF ROTATING ELECTRICAL MACHINES



79 01 87 2

Fig. 3.7


DC MOTOR WEIGHT CHARACTERISTICS
MOTOR WEIGHT, LBM
1000000
100000
10000
1000
100
100,000 kg
10,000
1000
FULL LOAD TORQUE FACTOR, HP/RPM
10^{-2}
10^{-1}
1.0
10
100
1000
10^{-1}
1.0
10.0
100.0KW/RPM
ASSUMED WEIGHT CHARACTERISTIC OF SUPERCONDUCTING DC MOTORS
ASSUMED WEIGHT CHARACTERISTIC OF SEGMAG MOTORS
INDUSTRIAL DRIP PROOF MOTORS
LAND TRANSPORTATION TRACTION MOTORS
OFF TH SHELF MOTORS
LEGEND
SPECIAL ORDER CONVENTIONAL MOTOR
SEGMAG II DESIGN
SUPERCONDUCTING HOMOPOLAR MOTOR
EXPERIMENTAL SUPERCONDUCTING HOMOPOLAR MOTOR
SUPERCONDUCTING HOMOPOLAR MOTOR DESIGNS

Specific Weights of Electrical Transmissions

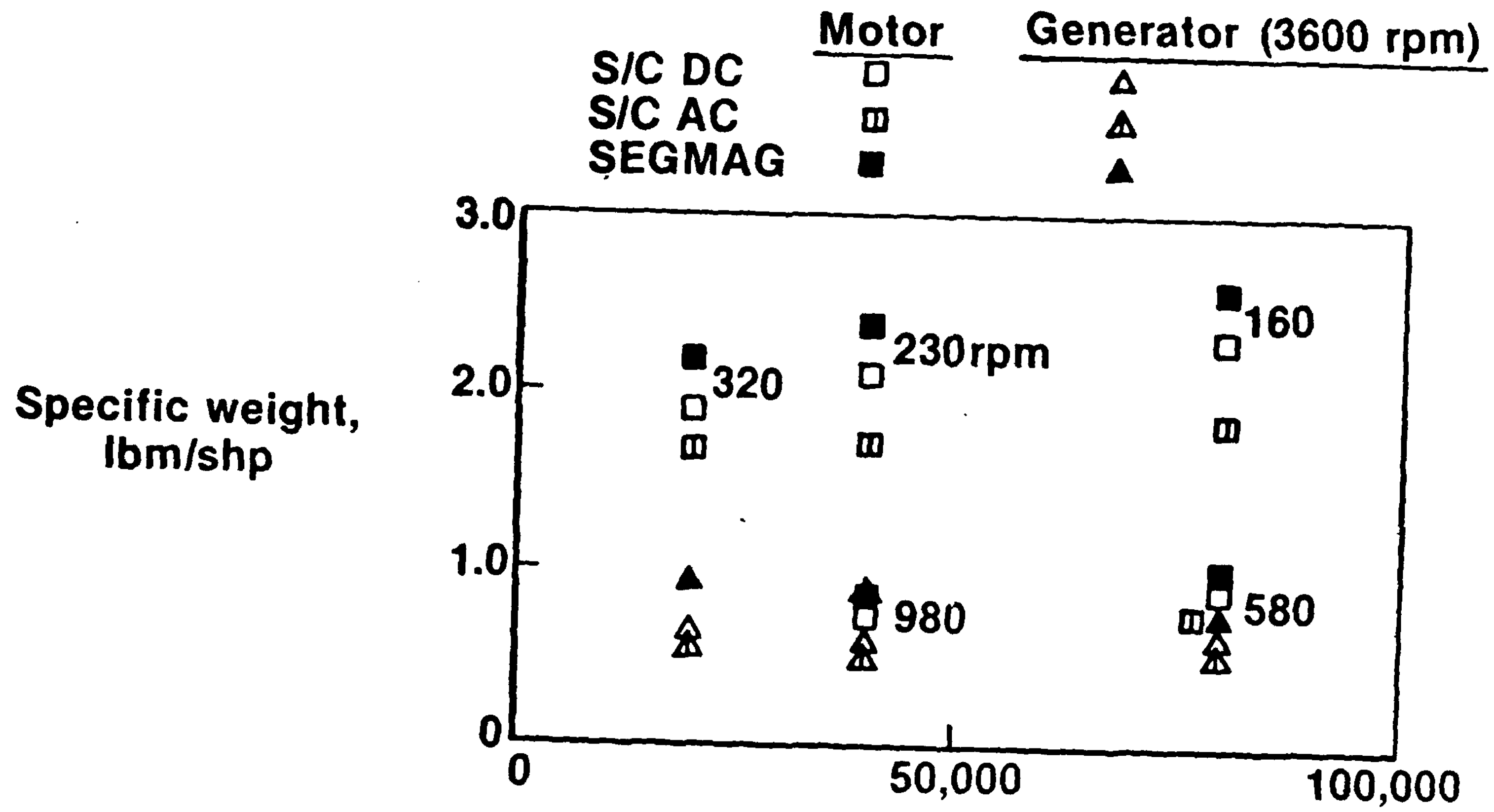


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Fig. 3.4

79-10-12-8

SELECTION MATRIX FOR ALTERNATIVE TRANSMISSION SYSTEMS

PRIME MOVER 59.7MW (80,000 SHP) FOSSIL-FIRED CLOSED-CYCLE HELIUM GAS TURBINE ENGINE (REF. 2.1)

INCOMPATIBLE   COMPONENT CAPACITY LIMITATION   NEED BOTH MECH. & ELEC. TRANSMISSIONS (HYBRID)

TRANSMISSION TYPE	HIGH SPEED DESTROYER INSTALLED POWER 160,000 SHP			CONVENTIONAL DESTROYER INSTALLED POWER 80,000 SHP		
DESCRIPTION	PROPULSION SYSTEM	2 THRUSTORS	4 THRUSTORS	PROPULSION SYSTEM	2 THRUSTORS	4 THRUSTORS
EPICYCLIC GEARBOX	2 UNITS	C1		1 UNIT		
OFFSET GEARBOX	2		C5	1	C9	
SEGMAG GENERATOR – SEGMAG GENERATOR – CONTROL – SEGMAG MOTOR – SEGMAG MOTOR	2	C2		1		
S.C. AC GENERATOR – CONTROL CYCLOCONV BRAKING – CRYOGENIC SYS – S.C. AC MOTOR	2	C3		1		
S.C. DC GENERATOR – CONTROL BRAKING – CRYOGENIC SYS – S.C. DC MOTOR	2	C4		1		
SEGMAG GENERATOR – SEGMAG GENERATOR – CONTROL – SEGMAG MOTOR, SEGMAG MOTOR	2		C6	1	C10	
S.C. AC GENERATOR – CONTROL RECTIFIER CYCLOCONV BRAKING – CRYOGENIC SYS – S.C. AC MOTOR, S.C. AC MOTOR	2		C7	1	C11	
[illegible] – CONTROL BRAKING – CRYOGENIC SYS – S.C. DC MOTOR, S.C. DC MOTOR	2		C8	1	C12	

Estimated CCGT-LWSPS R&D Cost Schedule

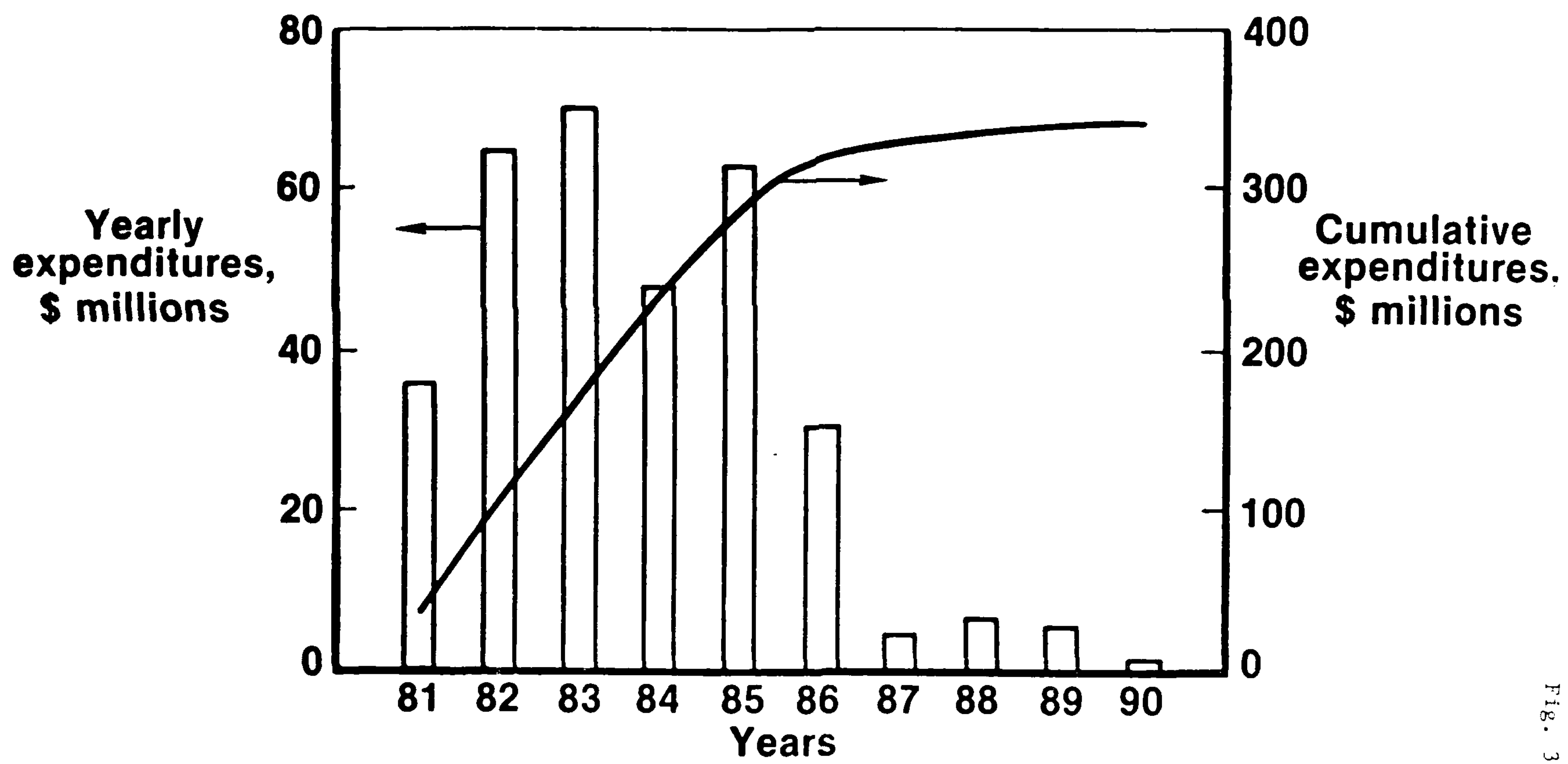

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Fig. 3.6

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